COMPARISON OF THE CONTROL ANTICIPATION PARAMETER AND THE BANDWIDTH CRITERION DURING THE LANDING TASK

THESIS

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David Andrew Kivioja

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List of Abbreviations and Symbols

Symbol	Definition
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
AGL	above ground level
AMRAAM	Advanced Medium-Range Air-to-Air Missile
AOA	angle of attack
$\bar{c}$	mean aerodynamic chord
CAP	Control Anticipation Parameter
C-H	Cooper-Harper
C_{l_α}	lift curve slope
$C_{m_{cl}}$	change in pitching moment coefficient due to a change in lift coefficient
$C_{m_{\dot{\Theta}}}$	change in pitching moment coefficient due to a change in pitch attitude rate
DAS	Data Acquisition System
dB	decibels
Drb	dropback
$e^{-\tau s}$	pilot's time delay
$e^{-\tau_\Theta s}$	higher order pitch attitude time delay
F_{a_s}	lateral stick force
F_{e_s}	longitudinal stick force
FPM	flight path marker
FRA	frequency response analysis

Symbol	Definition
g	acceleration due to gravity
G	plant
HQDT	Handling Qualities During Tracking
HUD	head-up display
ILS	instrument landing system
I_y	moment of inertia about the y-body axis
K	transfer function gain
K_Θ	pitch attitude transfer function gain
KIAS	knots indicated airspeed
KTAS	knots true airspeed
kts	knots
LOES	lower order equivalent system
lm	log magnitude
l_t	tail arm, 0.25 $\bar{c}$ of tail to 0.25 $\bar{c}$ of wing
max	maximum
MFD	multi-function display
MIL-STD	military standard
min	minimum
MSL	mean sea level
n/α	change in normal load factor due to a change in angle of attack
OAT	outside air temperature
PA	pressure altitude
PIO	pilot induced oscillation
PTI	programmed test input

List of Abbreviations and Symbols (Continued)

Symbol	Definition
q	dynamic pressure
q_{peak}	peak pitch rate
q_{ss}	steady-state pitch rate
s	Laplace variable
S	wing reference area
$1/T_{\Theta_1}$	high frequency pitch attitude zero
$1/T_{\Theta_2}$	low frequency pitch attitude zero
TPS	USAF Test Pilot School
USAF	United States Air Force
V	true airspeed
VHF	very high frequency
VHS	videocassette
VISTA	Variable-Stability Inflight Simulator Test Aircraft
VSS	variable stability system
W	aircraft weight
$\Delta n_{z_{ss}}$	change in steady-state normal acceleration about the instantaneous center of gravity
α	angle of attack
Δ	step size
δ	deflection of control surface
δ_{a_s}	lateral stick position
δ_e	deflection of the stabilator

List of Abbreviations and Symbols (Concluded)

Symbol	Definition
$\delta_{e_{cmd}}$	commanded stabilator position
$\delta_{e_{pos}}$	actual stabilator position
δ_{e_s}	longitudinal stick position
Φ_1	phase angle at ω_1
γ	aircraft flight path angle
Θ	aircraft pitch attitude
$\ddot{\Theta}_0$	aircraft initial pitching acceleration about the instantaneous center of gravity
$\Theta_{2\omega_{180}}$	pitch attitude phase at twice ω_{180}
ρ	air density
τ_Θ	lower order equivalent system time delay
τ_p	phase delay
ω	frequency
ω_{sp}	undamped short period natural frequency
ω_{ph}	undamped phugiod natural frequency
ω_{BW}	bandwidth frequency
ω_{BW_G}	gain limited bandwidth
ω_{BW_p}	phase limited bandwidth
ω_1	twice the ω_{180} frequency
ζ_{sp}	short period damping ratio
ζ_{ph}	phugoid damping ratio

Abstract

Many handling qualities criteria have been developed which predict pilot opinion of landing aircraft. MIL-STD-1797A, *Flying Qualities of Piloted Aircraft*, lists six different criteria. However, applying all six criteria to one aircraft can lead to conflicting results. The Air Force Institute of Technology (AFIT) along with the Flight Dynamics Laboratory have conducted research to evaluate differences among the handling qualities criteria in MIL-STD-1797A. The overall objective of this thesis was to determine similarities and discrepancies between the Control Anticipation Parameter (CAP) and bandwidth criteria, and to evaluate the advantage of including a dropback criterion with the bandwidth criterion. Results of this research will be used to derive a more clear-cut, generally acceptable, comprehensive flying qualities criteria predicting pilot opinion for the next revision of MIL-STD-1797A. Research was conducted in two phases. Phase I was conducted at AFIT. There the CAP domain was mapped onto the bandwidth and bandwidth with dropback criteria revealing where the criteria agreed and disagreed. Phase II was conducted at the USAF Test Pilot School. The test team used the Variable-Stability In-Flight Simulator Test Aircraft (VISTA) to simulate aircraft and obtain actual pilot opinion in the areas of agreement and conflict found in Phase I.

COMPARISON OF THE CONTROL ANTICIPATION PARAMETER AND THE BANDWIDTH CRITERION DURING THE LANDING TASK

I. Introduction

1.1 Motivation for Research

Due to advances in aircraft control, various handling qualities criteria have been developed which attempt to predict pilot opinion of highly augmented aircraft. However, in many instances these criteria do not predict the same pilot opinion. The Flight Dynamics Laboratory along with the Air Force Institute of Technology (AFIT), at Wright-Patterson Air Force Base, Ohio, have conducted research to determine and resolve differences among the handling qualities criteria outlined in MIL-STD-1797A [1, 2 and 3]. The results of this research will be used to derive a more clear-cut, generally acceptable, comprehensive flying qualities criteria for the next revision of MIL-STD-1797A.

This thesis complimented the Flight Dynamics Laboratory's and AFIT's research efforts. The research determined and evaluated the similarities and discrepancies between the Control Anticipation Parameter (CAP), the bandwidth criterion, and a proposed dropback criterion for aircraft in the landing phase of flight. Phase I of this thesis was conducted at AFIT and determined areas of agreement and conflict for typical F-16 and Learjet type aircraft. Phase II was conducted at the USAF Test Pilot School. During this

phase, a flight test was conducted gathering quantitative and qualitative pilot opinion using the NF-16D Variable-Stability Inflight Simulator Test Aircraft (VISTA) as the host aircraft. This aircraft simulated handling qualities of aircraft throughout the CAP, bandwidth and dropback criteria. Pilot opinion of these variable stability system (VSS) configurations were used determining which criterion had the best correlation to pilot opinion and which area—agreement or disagreement—had the best correlation to pilot opinion.

1.2 Research Objectives

The overall objective of this thesis was to determine and evaluate the similarities and differences in predicting pilot opinion using the CAP and bandwidth criterion for aircraft in the landing phase of flight. These criteria were defined as presented in MIL-STD-1797A, *Flying Qualities of Piloted Aircraft* [16]. A proposed dropback criterion augmenting the bandwidth criterion was also evaluated determining its effectiveness [17 - 20].

Research for Phase I assumed the F-16 and Learjet type aircraft could be accurately approximated by a second order short period transfer function using a higher order time delay of 0.100 second. Phase I specific objectives were accomplished for both types of aircraft and were:

1. Determine the areas of agreement and conflict between CAP, bandwidth, and bandwidth augmented by the proposed dropback criterion.

2. Determine the minimum short period undamped natural frequency ($\omega_{sp}|_{min}$) and minimum load factor per angle of attack ($n/\alpha|_{min}$) for CAP Level 1 and 2 as defined in MIL-STD-1797A.

3. Map the boundary between acceptable and excessive dropback onto the CAP space. (As will be shown in Chapter 2, the dropback line was that line where, if crossed going from acceptable dropback to excessive dropback, one level must be added to the bandwidth criterion while the CAP level remained the same. In other words, if an aircraft predicted to be Level 1 by the bandwidth criterion without dropback exhibits excessive dropback, it should be predicted Level 2 by bandwidth using dropback).

4. Map the boundary between acceptable and excessive dropback onto the bandwidth space.

5. Determine regions in CAP where the bandwidth criterion was gain limited and phase limited.

6. Determine regions in CAP where the pitch attitude Bode magnitude plot was monotonicly decreasing and non-monotonic.

7. Determine regions in CAP where the discontinuity in bandwidth exists. (As will be shown in Chapter 3, this discontinuity manifested itself as a line in the

CAP space—termed the "jump line." The jump line was a line where, if ω_{sp} was increased or the short period damping ratio (ζ_{sp}) was decreased, the bandwidth would instantaneously go from a high frequency to a low frequency).

The Phase II specific objectives of this research were:

1. Obtain and evaluate qualitative and quantitative pilot opinion and Cooper-Harper Pilot Ratings in those areas where the criteria agreed and disagreed.

2. Obtain and evaluate qualitative and quantitative pilot opinion and Cooper-Harper Pilot Ratings approaching the $\omega_{sp}|_{min}$ region.

3. Obtain and evaluate qualitative and quantitative pilot opinion and Cooper-Harper Pilot Ratings approaching the dropback line.

4. Obtain and evaluate qualitative and quantitative pilot opinion and Cooper-Harper Pilot Ratings approaching the jump line.

5. Evaluate pilot opinion trends about those points satisfying Phase II objectives 1 through 4.

6. Collect and archive supporting data for future handling qualities analyses for AFIT and the Flight Dynamics Laboratory.

Pilot opinion was quantified using the Cooper-Harper and pilot induced oscillation (PIO) rating scales based on the desired and adequate criteria set forth in Chapter 5. These rating scales are presented in Appendix A, Figure 33 and Figure 34. Qualitative pilot opinion was gathered after each landing event. Included in these comments were weather effects such as winds and turbulence, with turbulence rated using the standard light, moderate and severe descriptors. Comments also included firmness of touchdown using soft, medium and firm descriptors. All Phase II specific objectives used the same evaluation criteria.

1.3 Literature Review

New handling qualities criteria have been developed to predict pilot opinion of landing aircraft. Many of the new handling qualities metrics are applicable to highly augmented aircraft [4 - 24]. The handling qualities parameters compared in this research effort were CAP, as defined in MIL-STD-1797A [16], and the bandwidth criteria, as defined in MIL-STD-1797A [16] and supplemented by the addition of a recommended dropback criterion [17 - 20]. As applied in this thesis, these three handling qualities criteria predicted pilot opinion through the aircraft's short term pitch response. MIL-STD-1797A states "the importance of the short-term pitch response reflects the high attention it has been given and the great need for further study to derive a clear-cut, generally applicable set of requirements" (16:171). In response to this, AFIT has continued research on the longitudinal handling qualities effects on pilot opinion ratings [1, 2, 3, 5, 6, 8 and 14].

The CAP criterion was developed to predict the precision a pilot could expect in controlling an aircraft's flight path (7:1). However, to apply this criterion for highly augmented aircraft, a lower order equivalent systems (LOES) match is required. The methodology, adequacy and idiosyncrasies of LOES matches with regard to the higher order aircraft have been the subject of many recent discussions in published literature [10, 12, 16, 18 and 20]. As a few of these publications indicate, there is some controversy on the applicability of using LOES matches and the CAP criterion to predict handling qualities of higher order aircraft.

In contrast to the CAP criterion which was developed for aircraft which have classical short period dynamics (20:44), many frequency domain criteria have been developed specifically for higher order aircraft [4, 11, 21 and 22]. Recently, a new time domain dropback criterion [17 - 20] has been proposed augmenting the bandwidth criterion [11 and 16]. This new metric attempts to identify aircraft which have abrupt pitch control, but lack pitch control precision.

A common thread throughout both the CAP and bandwidth requirements was that each used the Cooper-Harper Pilot Rating Scale to quantify an aircraft's handling qualities (see Figure 33 for the Coop-Harper Pilot Rating Scale). Reference 9 details the ramifications on safety for corresponding Cooper-Harper ratings. MIL-STD-1797A further broke the Cooper-Harper Pilot Rating Scale into: Cooper-Harper rating 1 - 3 ⇨ Level 1; 4 - 6 ⇨ Level 2; and 7 - 9 ⇨ Level 3 (16:86). MIL-STD-1797A then defined each handling qualities level as:

> Level 1—Satisfactory. Flying qualities clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation.
>
> Level 2—Acceptable. Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
>
> Level 3—Controllable. Flying qualities such that the aircraft can be controlled in the context of the mission flight phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both. (16:85)

1.4 General Background Information

MIL-STD-1797A defined the landing phase as those maneuvers which require precise flight path control using gradual maneuvers during the terminal phases of flight. Precise tracking tasks generally require high open loop system stability and high short period damping, ζ_{sp}. This enables the pilot to track high frequency inputs and reject disturbances without unacceptable oscillations due to low ζ_{sp} and closed loop stability (11:45).

The landing phase can further be broken into the approach and flare phases (13:536). During the approach, emphasis is placed on pitch attitude control while the flare emphasizes flight path control. Two general techniques are used during the landing phase of flight. They are the "frontside" and "backside" techniques referring to which side of the power curve the aircraft is operating within. The frontside technique uses the pitch attitude of the aircraft, Θ, to control the touch-down point or flight path angle, γ, and throttle position to control airspeed. The backside technique uses Θ to control airspeed

while γ is controlled by throttle position. In other words, the pilot uses the pitch manipulator (commonly the elevator or canard) to control airspeed and throttle position to control the touch-down point. Figure 1 shows the definitions of the pitch attitude angle and flight path angle.

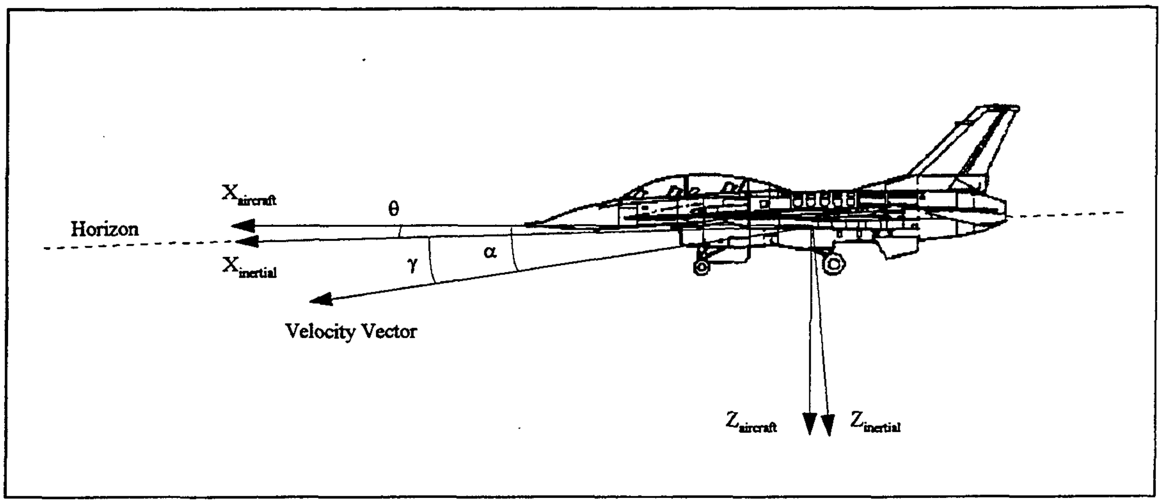


Figure 1 Aircraft Axis System

As the aircraft approaches the ground, the pilot reduces the throttle to idle and gradually shifts control inputs so the pitch manipulator controls the slower γ loop, while the faster Θ loop becomes an outer, sub-dominant loop. The pilot's goal is to smoothly transition γ to zero at wheel touch-down. Pilot-induced-oscillations and degradation of

pilot opinion are most likely to occur during this transitioning part of the landing task (13:535, 23:49).

1.5 Report Organization

This thesis is organized with Chapter 1 providing the introduction, motivation, objectives and landing phase definition for the research. Chapter 2 provides the theory behind the CAP, bandwidth and dropback criteria. Chapter 3 then presents the method behind the mappings between the various criteria used during Phase I while Chapter 4 presents the results of the mappings. Chapter 5 details the flight test theory and techniques used during Phase II with Chapter 6 presenting the results. Finally, Chapter 7 brings Phases I and II together.

II. Theory

2.1 The Control Anticipation Parameter

The Control Anticipation Parameter (CAP) was defined as the ratio of an aircraft's initial pitching acceleration, $\ddot{\Theta}_0$, to its change in steady-state normal acceleration, $\Delta n_{Z_{ss}}$, where all accelerations were measured about the instantaneous center of gravity. For aircraft with classical longitudinal second order responses, this can mathematically be represented as

$$\mathrm{CAP} \equiv \frac{\ddot{\Theta}_0}{\Delta n_{Z_{ss}}} = \frac{W\bar{c}C_{m_{C_L}} + \frac{1}{4}S\bar{c}^2\rho g C_{m_{\dot{\Theta}}}}{-I_Y\left[1 + \dfrac{C_{m_{C_L}}}{l_t/\bar{c}}\right]} \tag{1}$$

$$\approx \frac{\omega_{sp}^2}{n/\alpha} \approx \frac{\omega_{sp}^2}{\dfrac{V}{g}\dfrac{1}{T_{\Theta_2}}} \quad \left(\frac{\mathrm{rad/sec}}{g}\right), \tag{2}$$

where

$W \equiv$ aircraft's total weight
$\bar{c} \equiv$ mean aerodynamic chord
$C_{m_{C_L}} \equiv$ change in pitching moment coefficient due to a change in lift coefficient
$S \equiv$ wing reference area
$\rho \equiv$ air density
$g \equiv$ acceleration due to gravity
$C_{m_{\dot{\Theta}}} \equiv$ change in pitching moment due to a change in pitch attitude rate
$I_y \equiv$ moment of inertia about the aircraft's y-body axis

$l_t \equiv$ tail arm, 0.25 $\bar{c}$ of tail to 0.25 $\bar{c}$ of wing
$\omega_{sp} \equiv$ undamped short period natural frequency
$n/\alpha \equiv$ the steady-state normal acceleration change per unit change in angle of attack for an incremental pitch control deflection at constant airspeed and Mach number
$V \equiv$ true airspeed
$1/T_{\Theta_2} \equiv$ high frequency pitch attitude zero.

The approximations of CAP in Equation 2 are derived using the longitudinal short period approximation and are developed in Reference 7.

The CAP criterion required aircraft which had more modes of motion than the classical short period and phugoid modes be reduced to a lower order equivalent system (LOES) as outlined in MIL-STD-1797A (16:175 - 182). The LOES, linearized match results in a classical, reduced order pitch attitude transfer function of the form:

$$\frac{\Theta(s)}{\delta_e(s)} = \frac{K_\Theta\left(s + 1/T_{\Theta_1}\right)\left(s + 1/T_{\Theta_2}\right)e^{-\tau_\Theta s}}{\left(s^2 + 2\zeta_{ph}\omega_{ph}s + \omega_{ph}^2\right)\left(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right)}, \tag{3}$$

where

$\delta_e \equiv$ deflection of pitch manipulator (commonly the elevator or canard)
$K_\Theta \equiv$ pitch attitude transfer function gain
$1/T_{\Theta_1} \equiv$ low frequency zero
$e^{-\tau_\Theta s} \equiv$ higher order pitch attitude time delay
$\zeta_{ph} \equiv$ phugoid damping ratio
$\omega_{ph} \equiv$ undamped phugoid natural frequency
$\zeta_{sp} \equiv$ short period damping ratio.

If the phugoid and short period modes are sufficiently separated, the short period can further be reduced to

$$\frac{\Theta(s)}{\delta_e(s)} \approx \frac{K_\Theta\left(s+1/T_{\Theta_2}\right)e^{-\tau_\Theta s}}{s\left(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2\right)}. \tag{4}$$

The magnitude of CAP gives the pilot an indication of the change in steady-state normal acceleration from the aircraft's initial pitching acceleration. This is essential because of the time lag between the pilot's input and the final steady-state normal acceleration. For example, aircraft with a large CAP have large initial pitching accelerations compared to the final steady-state normal accelerations. Thus, longitudinal control inputs which change the pitch attitude cause pilots to sense large initial pitching accelerations. In this circumstance, pilots tend to reduce or reverse control inputs to avoid the anticipated large normal acceleration. As a result, pilots typically undershoot the desired flight path and tend to rate the aircraft as being fast, abrupt, and sensitive.

On the other hand, a small CAP means the initial pitching acceleration is low compared to the final steady-state normal load factor. Longitudinal control inputs changing the pitch attitude cause pilots to sense low initial pitching accelerations. Thus, pilots would increase control inputs to achieve the desired pitching acceleration. However, due to the lag between the initial pitching acceleration and the steady-state normal acceleration, a large steady-state normal acceleration results and the desired flight path would be overshot. Pilot comments would typically classify the aircraft as being sluggish. Therefore, the magnitude of CAP can be used as an indirect measure of pilot opinion as the aircraft is flown along the glide slope (7:6).

The landing phase CAP boundaries, as presented in MIL-STD-1797A, are shown in Figure 2. CAP in the figure was defined from Equation 2 using a LOES match. Levels 1, 2 and 3 correspond to the definitions presented in Section 1.3 and to the Cooper-Harper Pilot Rating Scale shown in Appendix A, Figure 33.

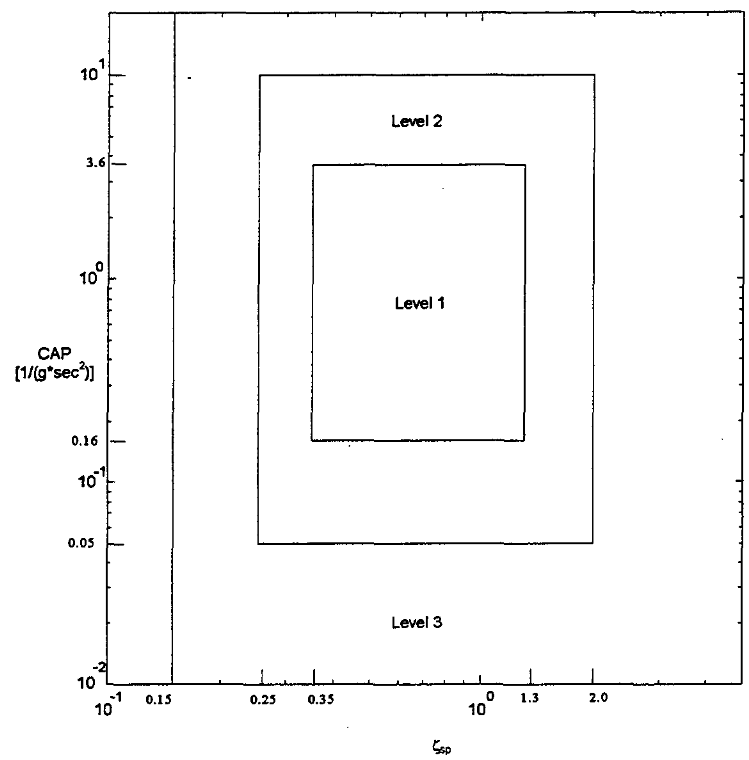


Figure 2 Landing Phase CAP Criterion

Figure 2 shows that for an aircraft to be rated as satisfactory, Level 1, CAP must be relatively large and the system's short period damping must be within the boundaries of

0.35 to 1.3. However, CAP cannot be too large, resulting in an over sensitive aircraft. Pilots generally do not like low ζ_{sp}, resulting in unwanted overshoots.

In addition to Figure 2, MIL-STD-1797A restricted ω_{sp}, n/α and τ_Θ in the landing task as specified in Table 1 and 2. Class in Table 1 refers to the classes of aircraft defined in MIL-STD-1797A (16:77). They include: Class I—small, light aircraft; Class II—medium weight, low-to-medium maneuverability aircraft; Class III—large, heavy low-to-medium maneuverability aircraft; and Class IV—high maneuverability aircraft.

Table 1 CAP Requirements on ω_{sp} and n/α—Landing Task

Class	Level 1		Level 2	
	$\omega_{sp}\|_{min}$ (rad/sec)	$n/\alpha\|_{min}$ (g/rad)	$\omega_{sp}\|_{min}$ (rad/sec)	$n/\alpha\|_{min}$ (g/rad)
I, II-C, IV	0.87	2.7	0.6	1.8
II-L, III	0.7	2.0	0.4	1.0

For Level 3, the time to double amplitude, based on the unstable root, shall be no less than 6 seconds. In the presence of any other Level 3 flying qualities, ζ_{sp} shall be at least 0.05 unless flight safety is otherwise demonstrated to the satisfaction of the procuring agency. (16:173)

Table 2 CAP Requirement on Time Delay—Landing Task

Handling Quality Level	Allowable Delay (sec)
1	0.10
2	0.20
3	0.25

(16:173)

In summary, CAP can be used to predict pilot opinion of an aircraft's longitudinal mode of motion. To make precise flight path adjustments, a pilot must be able to anticipate the ultimate response from the instantaneous motion of the aircraft. Longitudinally, the instantaneous motion is sensed through pitching accelerations. Thus, "the amount of instantaneous angular pitching acceleration per unit of steady state normal acceleration is...an index of the strength of the anticipation signal received by the pilot" (7:5).

2.2 The Bandwidth Criterion

The bandwidth criterion defined bandwidth frequency in a flying qualities sense. In this definition, an aircraft's bandwidth frequency was the highest open-loop cross over frequency attainable with good closed-loop dynamics. Bandwidth frequency defined in this way can be used to measure the speed of response a pilot can expect when tracking with rapid control inputs. The magnitude of an aircraft's bandwidth frequency also indicates how tightly the pilot is able to "...close the loop without threatening the stability of the pilot/vehicle system; it is a measure of tracking precision and disturbance rejection." (11:45)

Classical control theory defines the bandwidth frequency, ω_{BW}, as that frequency where the closed loop magnitude is 3 dB down from the low frequency value, or 0 dB when the closed loop system is low pass. When the system is first order, ω_{BW} is the open

loop's crossover frequency. Thus, ω_{BW} can be a good measure of the closed-loop system's time response (11:45).

The bandwidth criterion, as defined in MIL-STD-1797A (16:225 - 236), was specifically developed for highly augmented aircraft which do not have traditional modes of motion. This criterion was derived from flight test results of the YF-16 Fighter Control Configured Vehicle. The YF-16 evaluated the effectiveness of independent control of ventral canards for side force generation and existing wing flaps for direct lift generation. Benefits of the bandwidth criterion are that it does not require a LOES match, nor does it rely on a pilot model.

The longitudinal bandwidth flying quality metric, ω_{BW}, was defined as the highest frequency where the open-loop system had at least a 45° phase margin and a 6 dB gain margin—both criteria must be met. This essentially judges the pilot's ability to double the gain or add a time delay without causing longitudinal instability. Note, the gain and phase margins are not defined in the classical way. The gain margin was not defined from encirclements of the -1 point at a phase angle of -180° on the system's Nyquist plot—the gain required to cause instability—due to the difficulty in defining the nominal gain. Therefore, a gain of 6 dB from the -180° frequency, ω_{180}, was chosen to indicate a doubling of the pilot's gain. The phase margin definition was derived from...

> the relationship between closed-loop damping and open-loop phase margin for an ideal open-loop plant ($G = Ke^{-\tau s}/s$ where τ is the pilot's time delay)...shown in Figure 3.... Based on a study of simulation data using pilot/vehicle analysis techniques, Reference [15] shows that a closed-loop damping ratio of 0.35 sets the approximate boundary between undesirable and desirable flying qualities...(11:45).

As illustrated in Figure 3, a damping ratio of 0.35 corresponds to an approximate phase margin of 45°. Again because of the difficulty in defining the nominal gain, the phase margin was defined as the frequency where the open-loop Bode plot has a phase angle of -135° (i.e. -180° + 45°). Using Figure 3 for higher order systems was justified since this criterion assumed the pilot would supply the needed leads and/or lags to make the system's response look like the response of K/s (11:48).

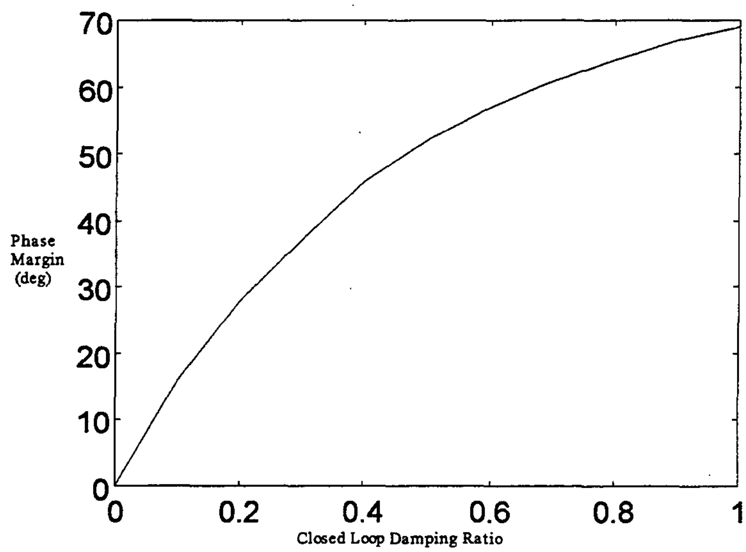


Figure 3 Phase Margin vs. Closed-Loop Damping for $G(s) = Ke^{-\tau s}/s$ (11:47)

Application of the bandwidth criterion is illustrated by a typical Bode plot shown in Figure 4. From the bandwidth definition, two bandwidth frequencies, ω_{BW_P} and ω_{BW_G}, must be examined. As defined, the phase margin bandwidth frequency, ω_{BW_P}, was that frequency where the phase was 45° more than -180°, or -135°. The gain margin

bandwidth frequency, ω_{BW_G}, was defined as that frequency where the gain was 6 dB more than the gain at a phase of $-180°$. By selecting the lowest ω_{BW_P} or ω_{BW_G} as the definition required, ω_{BW} for this example was equal to ω_{BW_G}.

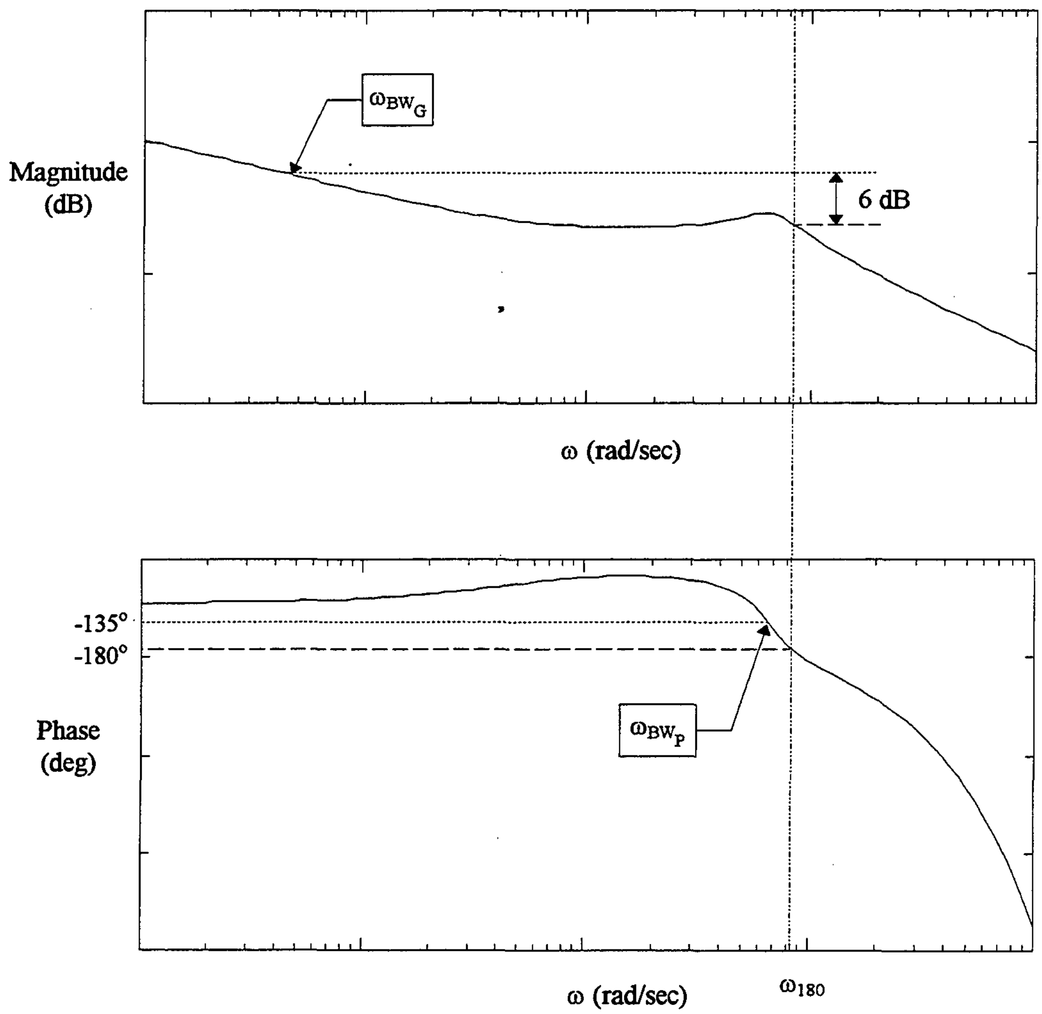


Figure 4 Definition of ω_{BW} from the Open-Loop Pitch Attitude Frequency Response (11:49)

The line defining ω_{BW_G} could either intersect the magnitude curve at one, two, or three locations depending on the location of ω_{180}. MIL-STD-1797A specifies that ω_{BW_G} is the highest frequency where the gain margin is at least 6 dB (16:225 - 226). Thus, the bandwidth with the highest frequency is identified as ω_{BW_G}.

The bandwidth criterion also requires the calculation of the system's high frequency time delay. This time delay can accurately be modeled by a pure time delay of the form $e^{-\tau_\Theta s}$, where τ_Θ was the system's high frequency time delay. By approximating the phase curve of the open-loop Bode plot as having a constant slope beyond ω_{180}, it is easily shown the time delay can be approximated by

$$\tau_\Theta \approx \tau_P = \frac{\Phi_1 - 180°}{57.3\omega_1}, \tag{5}$$

where $\omega_1 = 2\omega_{180}$ and Φ_1 is the phase at this frequency (16:228).

The longitudinal bandwidth criterion is shown in Figure 5 for aircraft in the landing phase of flight. This figure shows boundaries which are currently in MIL-STD-1797A (solid lines) and proposed bandwidth boundaries (dashed lines) which are recommended for inclusion in the next revision of MIL-STD-1797. The proposed bandwidth boundaries are valid only when applied along with the dropback criterion and are developed in References 17 through 20. Again, handling qualities levels correspond to the Cooper-Harper Pilot Rating Scale and the definition laid forth in Section 1.3.

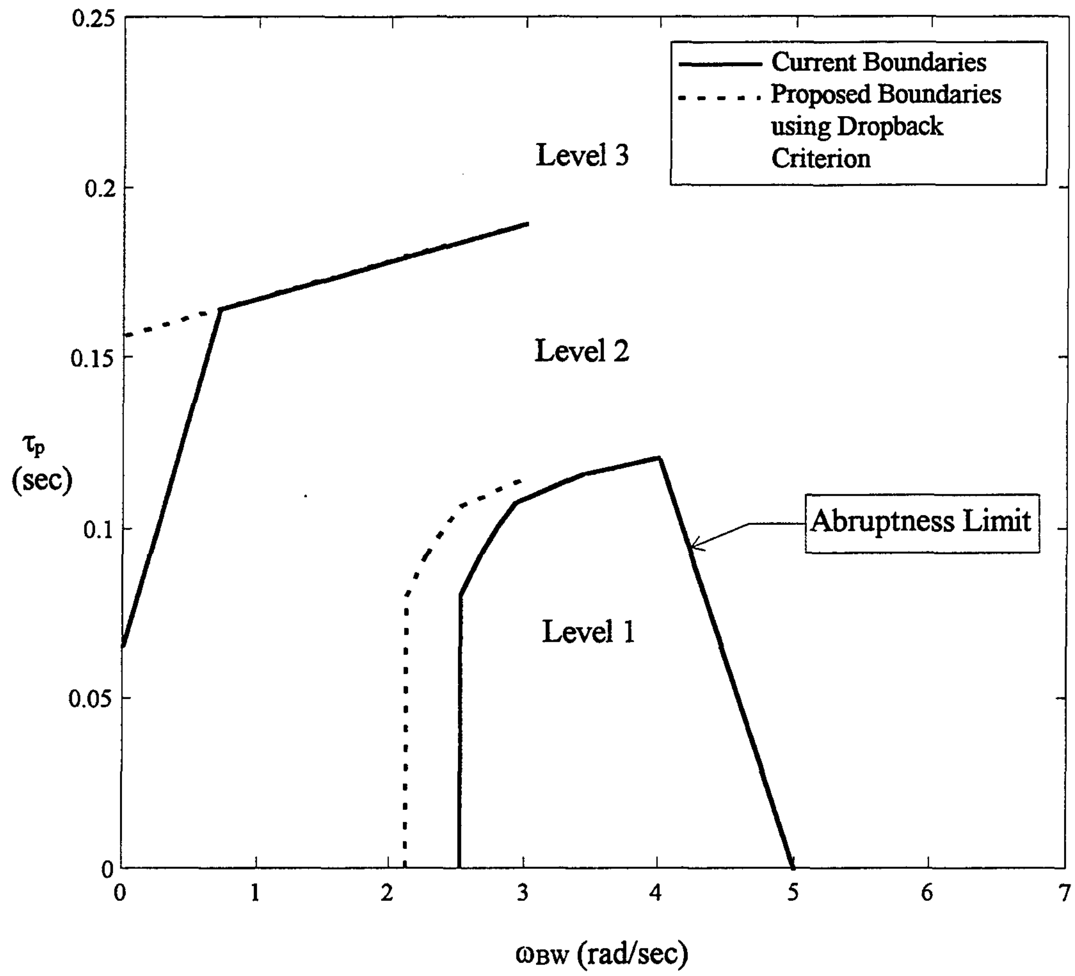


Figure 5 Landing Phase Bandwidth Criterion

From a pilot's point of view, aircraft with high bandwidth frequencies tend to have crisp, rapid, and well damped responses while aircraft with low bandwidth frequencies tend to wallow and have sluggish responses (11:49). In contrast to the proposed boundaries, flight test results indicate there is an upper limit on bandwidth frequency. As ω_{BW} is increased beyond 4 to 5 rad/sec, pilots have difficulty controlling the aircraft along the desired flight path in the presence of disturbances. If the aircraft does not attenuate

frequencies above this range, pilots may rate the aircraft's flying qualities as being poor. This was the reason the abruptness limit was placed in the current MIL-STD-1797A's definition of bandwidth. As will be shown in the next section, application of the proposed dropback criterion indirectly sets an upper limit on ω_{BW}.

2.3 The Dropback Criterion

The dropback criterion, as defined in References 17 through 20, has been recommended for inclusion in MIL-STD-1797A augmenting the proposed boundaries of the bandwidth criterion (see dashed boundaries on Figure 5). This new dropback criterion "...is a measure of the mid-frequency response to attitude changes.... Excessive dropback results in pilot complaints of abruptness and lack of precision in pitch control—complaints common also to aircraft with excessive values of pitch attitude bandwidth" (18:22).

As seen from Figure 6(a), the dropback criterion is based upon the time response of the aircraft due to a pitch manipulator input. The criterion requires a step pitch manipulator input, δ_e, be applied until a steady state pitch rate, q_{ss}, is reached; then the input is taken out. This type of input is referred to as a "box car input." The maximum pitch rate, q_{peak}, is defined to be the maximum pitch rate attained during the input. Dropback, Drb, is defined to be the difference between the maximum pitch attitude and the steady-state pitch attitude once the input is taken out. Both Drb and q_{peak} are normalized by q_{ss} so there was no dependency on the length or size of the input.

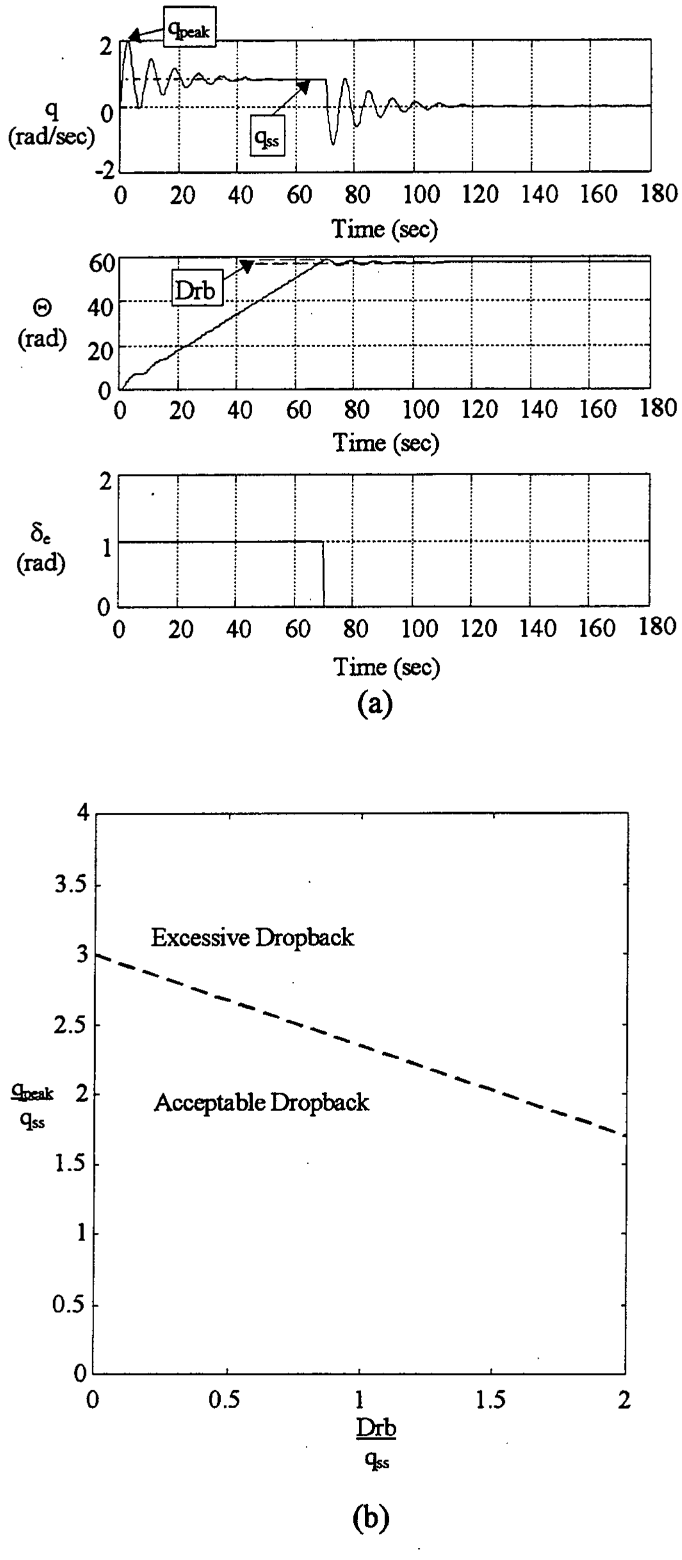


Figure 6 Dropback Criterion Definition

Historical flight test results show that when the normalized values of q_{peak}/q_{ss} and Drb/q_{ss} are plotted onto Figure 6(b) a correlation in pilot opinion exists. If the data point lay above the line, excessive dropback exists indicating abruptness or lack of pitch attitude precision. In the areas of excessive dropback, the criterion requires adding one to the level predicted by the bandwidth criterion. Correlation of pilot opinion was not strong enough to warrant usage of the dropback criterion alone. However, when coupled with the bandwidth criterion, historical data show correlation of pilot opinion increased.

As stated before, pilots have difficulties controlling aircraft with high ω_{BW}'s in the presence of disturbances since high frequencies are not attenuated. Studies show the dropback criterion and the "Abruptness Limit" account for poor handling qualities due to high ω_{BW}'s [18]. In other words, the dropback criterion and "Abruptness Limit" both try to characterize the same type of aircraft behavior. This was the justification for removing the "Abruptness Limit" when using the proposed dropback boundaries as shown in Figure 5.

2.4 Summary

In conclusion, the CAP and bandwidth criteria can be used to predict pilot opinion of aircraft in the landing phase of flight. CAP was based upon the aircraft's true airspeed, high frequency zero, short period natural frequency, and short period damping ratio. The bandwidth criterion, when coupled with the dropback criterion, was based upon the aircraft's open loop frequency and time responses. When applied separately, each criterion had reasonable correlation to historical pilot opinion. However, both criteria did

not predict the same pilot opinion over all possible aircraft responses as will be shown in Chapters 3 and 4.

III. Approach

3.1 Mapping CAP onto the Bandwidth Criterion

The objective of this thesis was to determine the similarities and differences between the CAP and bandwidth criteria during the landing phase of flight. This objective could be accomplished by either mapping the CAP domain onto the bandwidth space, or by mapping the bandwidth domain onto the CAP space. Each method would illustrate the intersection of both criteria and satisfy the objective.

By virtue of the short period magnitude and phase equations a distinct point in CAP mapped to an unique point in the bandwidth space, however, a distinct point in the bandwidth domain did not necessarily map to an unique point in the CAP space. To illustrate this, looking first at the mapping of CAP onto the bandwidth space, the magnitude and phase equations for the short period transfer function, Equation 4, were

$$\left|\frac{\Theta}{\delta_e}\right| = \mathrm{lm}\left(\frac{\sqrt{\omega^2 + \left(\frac{1}{T_{\Theta_2}}\right)^2}}{\omega\sqrt{\left(\omega_{sp}^2 - \omega^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega^2}}\right) \text{ (dB)} \tag{6}$$

$$\angle\frac{\Theta}{\delta_e} = \arctan\left(T_{\Theta_2}\omega\right) - \tau_\Theta\omega - \frac{\pi}{2} - \arctan\left(\frac{2\zeta_{sp}\omega_{sp}\omega}{\omega_{sp}^2 - \omega^2}\right) \text{ (rad),} \tag{7}$$

where $lm(\cdot) \equiv 20\log_{10}(\cdot)$ and $K_\Theta = 1$. Using Equation 2 and specifying a distinct point in the CAP domain for a particular aircraft (i.e. ω_{sp}, ζ_{sp}, $1/T_{\Theta_2}$, true airspeed, and τ_Θ specified), all variables other than ω in Equations 6 and 7 were defined. Of course, ω was the independent variable in constructing the Bode magnitude and phase plots of the transfer function. By defining an unique transfer function for the specific point in the CAP domain, Equations 6 and 7 become unique as does the system's time response and dropback criterion. Hence, determination of the bandwidth criterion was unique when mapping the CAP domain onto the bandwidth space.

The second approach achieving the objective would be to map the bandwidth domain onto the CAP criterion. When doing this, a specific point in the bandwidth domain uniquely defined τ_p and ω_{BW} as seen in Figure 5. Through the definition of bandwidth, the governing equations were:

$$\tau_p = \frac{-\Theta_{2\omega_{180}} - \pi}{2\omega_{180}}, \tag{8}$$

from Equation 5;

$$-\pi = \arctan\left(T_{\Theta_2}\omega_{180}\right) - \tau_\Theta\omega_{180} - \frac{\pi}{2} - \arctan\left(\frac{2\zeta_{sp}\omega_{sp}\omega_{180}}{\omega_{sp}^2 - \omega_{180}^2}\right), \tag{9}$$

defining the frequency at the -180° phase point, ω_{180};

$$\Phi_{2\omega_{180}} = \arctan\left(T_{\Theta_2} \cdot 2\omega_{180}\right) - 2\tau_{\Theta}\omega_{180} - \frac{\pi}{2} - \arctan\left(\frac{2\zeta_{sp}\omega_{sp} \cdot 2\omega_{180}}{\omega_{sp}^2 - 4\omega_{180}^2}\right), \quad (10)$$

defining the phase at twice the ω_{180} frequency, $\Phi_{2\omega_{180}}$;

$$-135°\left(\pi/180\right) = \arctan\left(T_{\Theta_2}\omega_{BW_P}\right) - \tau_{\Theta}\omega_{BW_P} - \frac{\pi}{2} - \arctan\left(\frac{2\zeta_{sp}\omega_{sp}\omega_{BW_P}}{\omega_{sp}^2 - \omega_{BW_P}^2}\right), \quad (11)$$

defining the phase limited bandwidth, ω_{BW_P};

$$\mathrm{lm}\left(\frac{\sqrt{\omega_{180}{}^2 + \left(1/T_{\Theta_2}\right)^2}}{\omega_{180}\sqrt{\left(\omega_{sp}^2 - \omega_{180}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{180}^2}}\right) + 6\,\mathrm{dB} = \mathrm{lm}\left(\frac{\sqrt{\omega_{BW_G}{}^2 + \left(1/T_{\Theta_2}\right)^2}}{\omega_{BW_G}\sqrt{\left(\omega_{sp}^2 - \omega_{BW_G}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{BW_G}^2}}\right)$$

(12)

defining the gain limited bandwidth, ω_{BW_G}; and

$$\mathrm{CAP} \approx \frac{\omega_{sp}^2}{\frac{V}{g}\frac{1}{T_{\Theta_2}}}, \quad (13)$$

as defined from Equation 2.

By definition, ω_{BW} was the lesser of ω_{BW_G} and ω_{BW_P}. It is easy to see that Equations 9 through 12 are non-linear, transcendental equations in ζ_{sp}, ω_{sp}, ω_{180}, ω_{BW_G}, and ω_{BW_P}. To map a distinct bandwidth point onto the CAP space, an aircraft zero, higher

order time delay, and true airspeed (i.e. $1/T_{\Theta_2}$, τ_Θ, and V) must be specified. With these variables fixed, there are five equations and four unknowns: ζ_{sp}, ω_{sp}, ω_{180}, $\Phi_{2\omega_{180}}$. Thus, an unique solution was not guaranteed—there could be zero, one or many solutions to the system of equations. Equation 13 was not used until ω_{sp} was found since it was a definition and had no influence on the solution of the four unknowns. Because of this non-uniqueness when mapping the bandwidth domain onto the CAP space, the method of mapping the CAP domain onto the bandwidth space was chosen.

Levels 1 and 2 of CAP were mapped onto the bandwidth domain enabling easy determination of the two criteria's intersection. Mapped also were lines which delineated the $\omega_{sp}|_{min}$ and $n/\alpha|_{min}$ boundaries from Table 1; the line which delineated excessive dropback; the line which delineated the switch between being phase limited, ω_{BW_P}, and gain limited, ω_{BW_G}—referred to as the gain limited line; and the line which defined the region where the transfer function's gain was purely monotonic—or where the slope of the transfer function's gain with respect to frequency did not change sign. As illustrated in Figure 7, depending upon ζ_{sp}, ω_{sp}, $1/T_{\Theta_2}$, and ω_{180} a discrete jump could occur in ω_{BW_G}. If this jump occurred when ω_{BW} equaled ω_{BW_G}, a discrete jump occurred in bandwidth. As will be shown later, there was a loci of points in the CAP space, which if crossed, resulted in this discrete jump in the bandwidth space. This mapping technique established clear boundaries and defined the intersection of the two criteria.

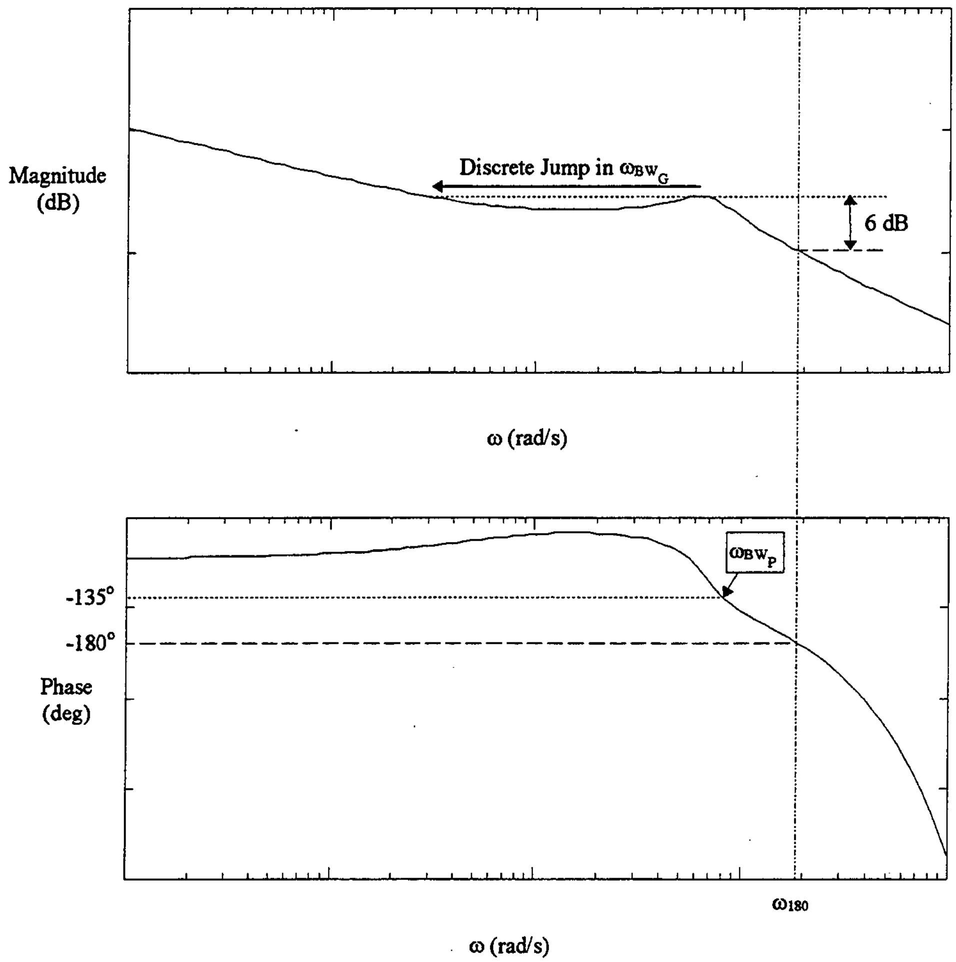


Figure 7 Gain Limited Bandwidth Discrete Jump

Mapping the CAP domain required fixing ζ_{sp} and ω_{sp} according to Figure 2. Equation 4 shows that $1/T_{\Theta_2}$ and τ_Θ must be specified. The high frequency zero, $1/T_{\Theta_2}$, was a fixed aerodynamic quantity and was aircraft specific. In anticipation of the flight test program, the variables $1/T_{\Theta_2}$ and τ_Θ were selected as nominal values for VISTA and the Learjet in the approach and landing configuration and are shown in Table 3. The

VISTA's approach and landing configuration was: Landing Gear - DOWN, Speed Brakes - OUT, 2,300 feet pressure altitude (PA), and 170 Knots True Airspeed (KTAS). The Learjet's approach and landing configuration was: Landing Gear - DOWN, Flaps - DOWN, and 125 KTAS.

The higher order time delay, τ_Θ, was chosen as 0.100 second since this defined the upper bound for CAP Level 1 as presented in Table 2. Equation 2 shows that to fix CAP, V must also be specified. Realistic values for each specific testbed's true airspeed were chosen and are shown in Table 4. The remainder of Chapter 3 describes the mapping approach for each of the aforementioned regions.

Table 3 Landing $1/T_{\Theta_2}$, τ_Θ Values and Flight Conditions for Phase I

Aircraft	$1/T_{\Theta_2}$	τ_Θ (sec)	Flight Condition
VISTA	0.51	0.100	170 KTAS, 2,300 ft PA
Learjet	0.60	0.100	125 KTAS

Table 4 Testbed Landing Airspeed for Phase I

Aircraft	Velocity Knots True Airspeed (KTAS)
VISTA	170
Learjet	125

3.2 Cooper-Harper Level Mapping

The first region mapped was the Cooper-Harper CAP Level 1 and Level 2 boundaries shown in Figure 2. Given a distinct point in the CAP domain—ω_{sp} and ζ_{sp} specified—true airspeed, aircraft zero and time delay all variables in Equation 4 were defined. Note, the value of K_{Θ} was arbitrary since its value had no influence on the bandwidth or dropback criteria. The short period transfer function, dropback, ω_{BW} and τ_p were easily calculated through use of the bandwidth and dropback definitions.

This method mapped the CAP boundaries onto the bandwidth space showing the intersection of the two criteria. The results of this mapping exposed a non-linear discrete jump in the bandwidth criterion. To identify and pinpoint this non-linearity, the dropback line, gain line and the line delineating a monotonic from a non-monotonic magnitude curve were mapped. Each mapped region narrowed the area where the discontinuity was likely to occur. A non-linear solution technique was finally employed defining a loci of points termed the "jump line," which if crossed, produced a discrete jump in the bandwidth domain.

This chapter presents the approach taken and the results of mapping the dropback line, gain line, non-monotonic line and jump line onto the bandwidth criterion. The results of mapping the CAP levels onto the bandwidth criterion are presented in a separate chapter. The reason for this is to present all regions in the CAP domain first so the reader has a clear understanding of each individual region. Once this is accomplished, the final mapping of the CAP domain onto the bandwidth and bandwidth with dropback criteria

will be presented in Chapter 4. Chapters 3 and 4 only present the mapping results for VISTA since this was the airframe used in Phase II of this research. The approach taken and mappings for the Learjet type aircraft are similar to that of VISTA and are presented in Appendix B.

3.3 $\omega_{sp}|_{min}$ and $n/\alpha|_{min}$ Limitations

MIL-STD-1797A set a minimum ω_{sp} and n/α for aircraft in the landing phase of flight as reflected in Table 1. With these restrictions, a minimum or maximum CAP was computed for each limit. These new limits redefined the CAP level boundaries.

The ω_{sp} limit was applied by use of Equation 2, reproduced below

$$\mathrm{CAP} \approx \frac{\omega_{sp}^{2}}{\frac{V}{g}\frac{1}{T_{\Theta_2}}}. \tag{14}$$

Given $\omega_{sp}|_{min}$ from Table 1 for the respective level, the landing true airspeed, and $1/T_{\Theta_2}$ for the respective aircraft, a minimum CAP was calculated. This new value of CAP set the new minimum boundary for the appropriate level. The results are shown in Table 5 and graphically as the shaded regions in Figure 8.

The n/α limit was applied by use of the approximation

$$n/\alpha \approx \frac{V}{g}\frac{1}{T_{\Theta_2}}. \tag{15}$$

Given the aircraft's true landing speed and $1/T_{\Theta_2}$, the minimum n/α for the aircraft was calculated. This calculated value was then compared to that listed in Table 1, ensuring the

value was greater than that listed. The calculated minimum n/α for VISTA was 4.55 g/rad. As seen in Table 1, this met the requirements of MIL-STD-1797A for Levels 1 and 2.

Table 5 MIL-STD-1797A Minimum CAP for VISTA

Handling Quality Level	Minimum CAP ($1/g*sec^2$)
1	0.17
2	0.08

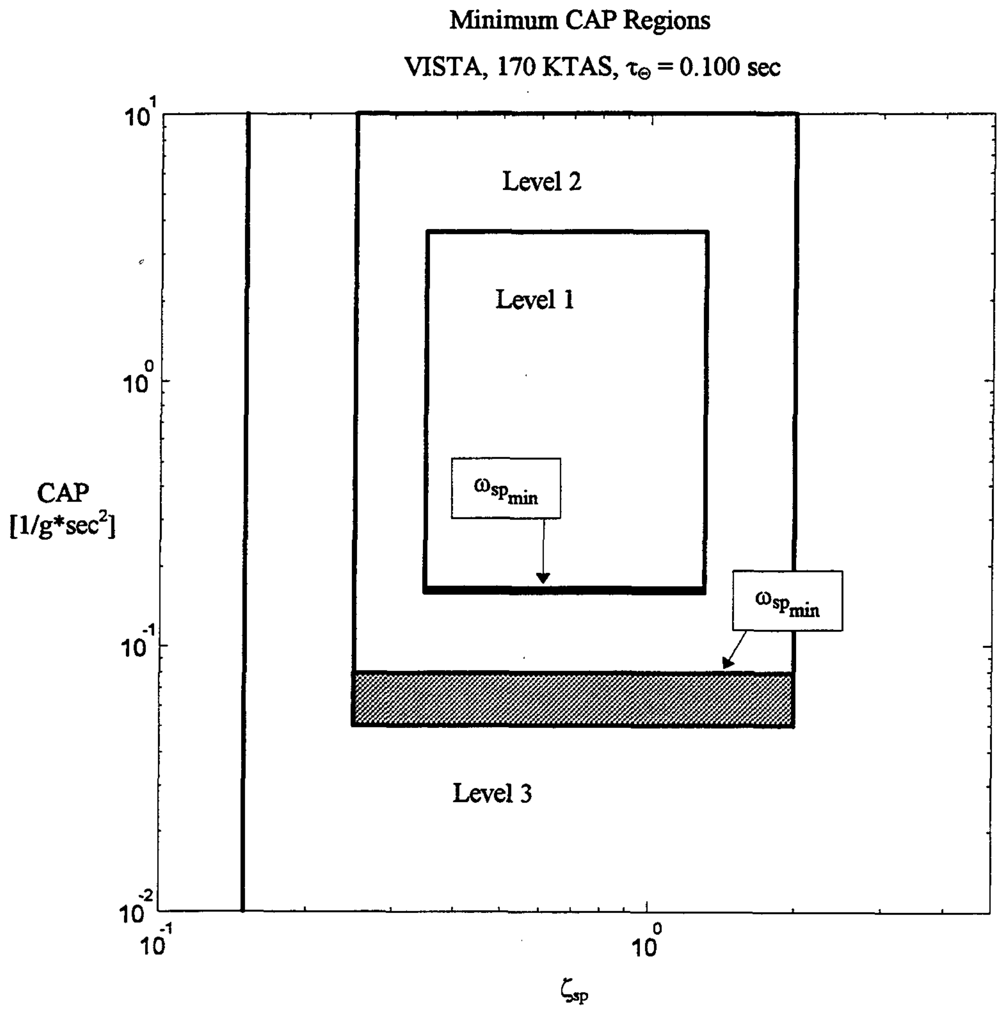


Figure 8 MIL-STD-1797A Minimum CAP for VISTA

3.4 Excessive Dropback Area

The region in CAP which had excessive dropback was identified. This region aided in identifying the location of the discrete jump. The area was defined in the CAP space by discretizing the CAP field for each aircraft and airspeed. At each discretized point the dropback definition was applied through Equation 4 using a boxcar input. This determined whether the point had acceptable or excessive dropback. Note that since a closed form solution for this region was not used, the boundaries of this region were only as accurate as the fineness of the discretized field.

A region of excessive dropback in the CAP space was identified as illustrated in Figure 9. Points which lay to the right of the excessive dropback line exhibited acceptable dropback while those which lay to the left exhibited excessive dropback. As required by the dropback definition, those points which had excessive dropback had their bandwidth handling qualities level increased by one.

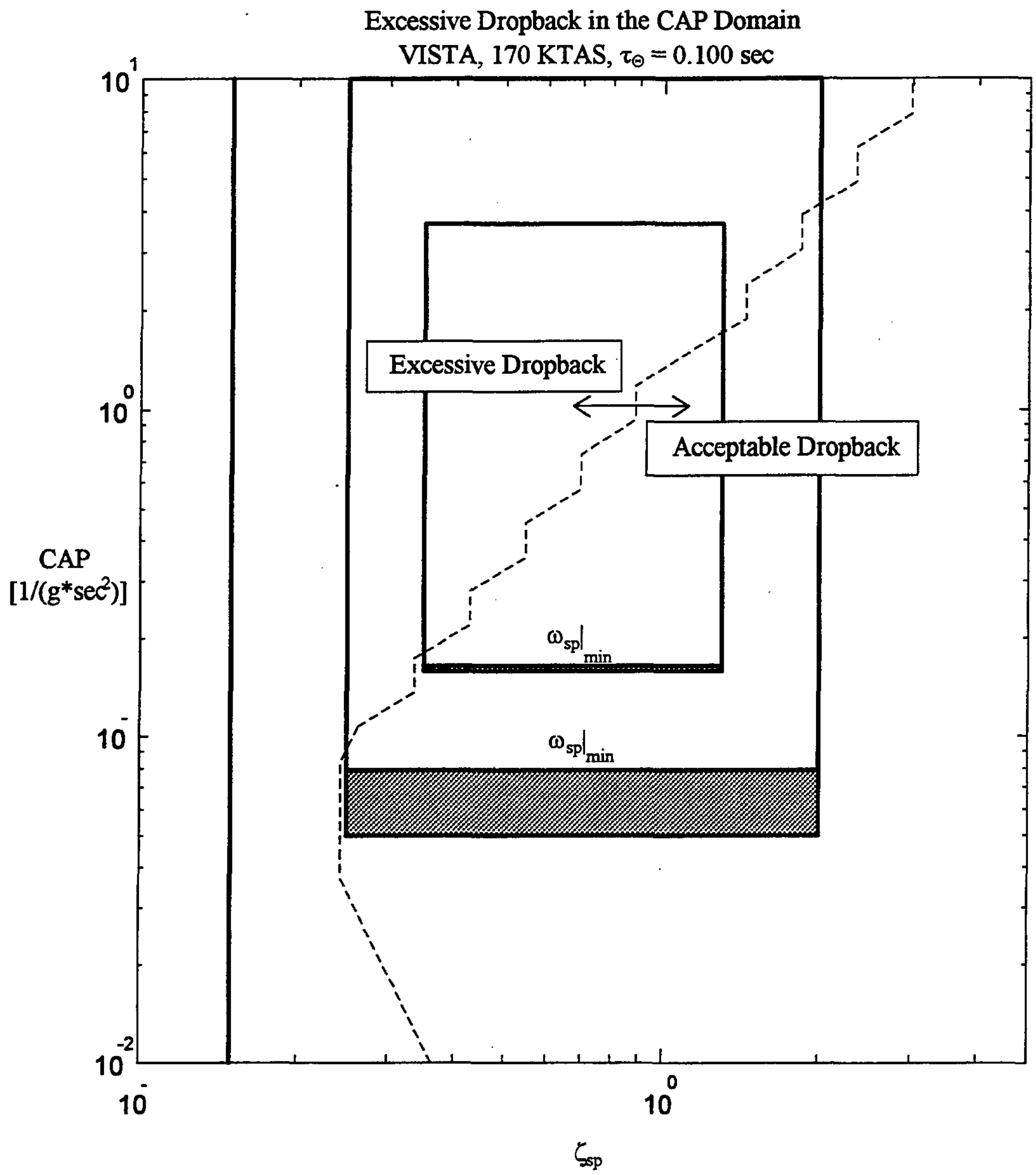


Figure 9 Excessive Dropback in the CAP Space

3.5 *Gain and Phase Limited Regions*

The regions in the CAP space where the bandwidth was defined by either the gain or phase definitions were mapped to narrow the possible areas of the jump discontinuity. Inspection of Equations 4 and 7 show the phase curve was always monotonically decreasing in the region of ω_{180}. Thus, ω_{BW_P} had no discontinuities. However, the same was not true of the gain curve as shown in Equations 4 and 6. It is easy to see from Figure 7, that a discontinuity could exist if the bandwidth jumped from a value close to ω_{sp} (i.e. near the second order pole's natural frequency and the possible local magnitude maximum) to a relatively low bandwidth. Because of this, the discontinuity always occurred when ω_{BW} equaled ω_{BW_G}.

The region where the bandwidth was defined by ω_{BW_G} was determined in much the same way as the excessive dropback region. The CAP field was discretized for each aircraft and airspeed. Each point in the CAP space was mapped onto the bandwidth space using Equation 4. This determined whether the point's bandwidth was gain or phase limited. From this mapping, regions in the CAP space which were gain or phase limited were identified. Again, the boundaries of the regions were only as accurate as the fineness of the discretized field.

The results of this mapping are presented in Figure 10. Points which were gain limited, defined by ω_{BW_G}, are represented by the lighter shaded regions. All other points were phase limited, defined by ω_{BW_P}. Points falling within the gain limited region satisfied one of the necessary conditions which defined the discontinuous jump line. The next

section will present the results of the other necessary condition for the jump line—having a non-monotonic gain curve.

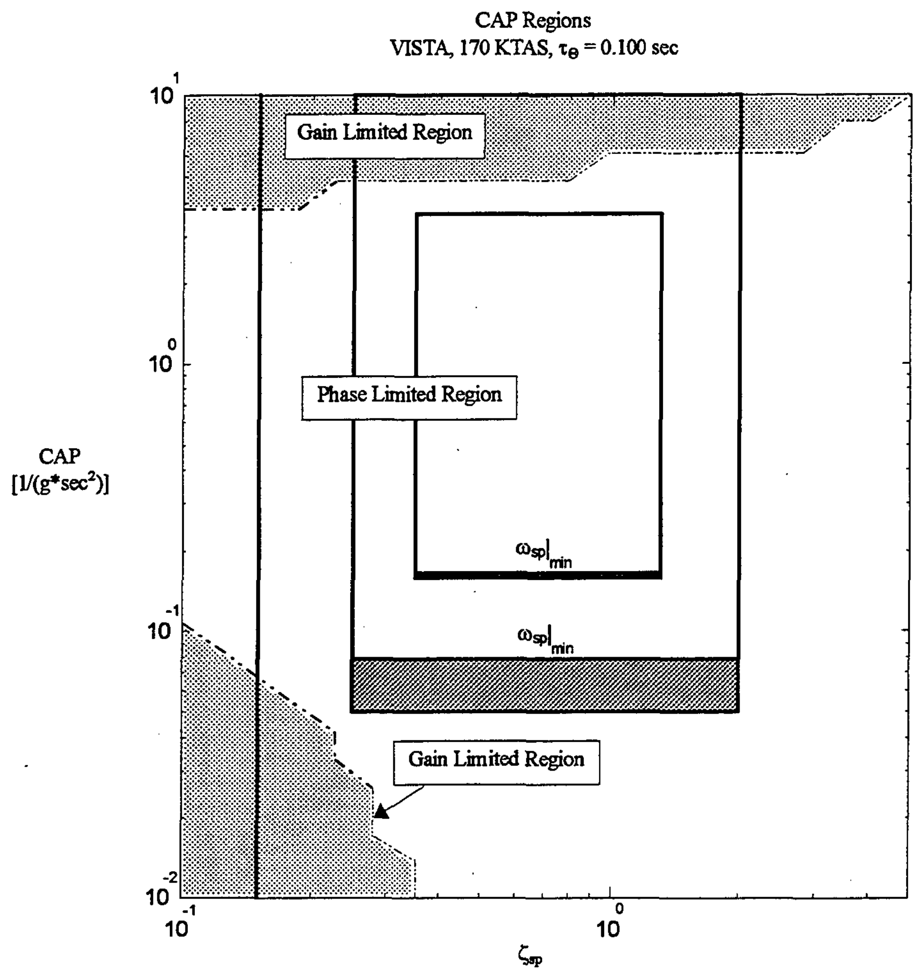


Figure 10 Gain and Phase Limited Regions in the CAP Space

3.6 Non-Monotonic Gain Curve

Further analysis of the discontinuity's nature revealed that being gain limited was a necessary condition, but it was not a sufficient condition for a jump in bandwidth. For instance, if the system was gain limited, but the magnitude was always monotonically decreasing, it was impossible to have a discontinuity. The necessary conditions for a discontinuity were to have a gain limited bandwidth and a non-monotonic gain curve—or the slope of the line changed signs with respect to frequency. As seen in Figure 7, the possibilities of having a non-monotonic gain curve was governed by the behavior near the second order pole's natural frequency. If there was no local peak in the region of ω_{sp}, the gain curve was monotonically decreasing for all frequencies eliminating the possibilities of a discontinuity. This local peak was governed by

$$\left|\frac{1}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2}\right| = -\ln\left(\sqrt{\left(\omega_{sp}^2-\omega^2\right)^2+4\zeta_{sp}^2\omega_{sp}^2\omega^2}\right). \tag{16}$$

Equation 16 shows that in the region where ω approached ω_{sp}, the peak became a function of ζ_{sp} and ω_{sp}—or purely a distinct loci of points in the CAP space.

This led to defining the region where the transfer function had a non-monotonic gain curve in the CAP space. This region was identified by discretizing the CAP field and determining whether each point's Bode magnitude curve was monotonically decreasing for all frequencies. The intersection of the regions where the magnitude was non-monotonic and where the bandwidth was gain limited further reduced the size of the

possible area where the discontinuity could exist. This region defined a necessary condition for the discontinuity, but it did not define a sufficient condition. For instance, if the bandwidth was located in a region as in Figure 4, a small change in either ω_{sp} or ζ_{sp} would not necessarily require the bandwidth to jump even though the magnitude was clearly non-monotonic and the bandwidth was gain limited. However, the intersection of the gain limited area and the non-monotonic area significantly reduced the area where the discontinuity could exist. It is this type of phenomena—being gain margin limited and having a non-monotonic Bode magnitude curve—which was characterized by historical data as exhibiting a degradation of handling qualities (16:231). Thus, the intersection of the gain limited area and the non-monotonic area indicate a possible region of poor handling qualities.

As shown in Figure 10, one of the necessary conditions which specified the region where a discontinuous jump could occur was defined by the bandwidth being gain limited. The other necessary condition was for the Bode magnitude curve to be non-monotonic. Figure 11 shows that if a point lay to the right of the line it had a monotonic gain curve while those which laid to the left had a non-monotonic gain curve. The intersection of the gain limited region and non-monotonic region, shown in Figure 12, defined a region where a potential existed for a discontinuous jump to occur. Points which lay within this area were gain margin limited and had a non-monotonic gain curve. Thus, as points approach this region aircraft handling qualities are predicted to deteriorate (16:231).

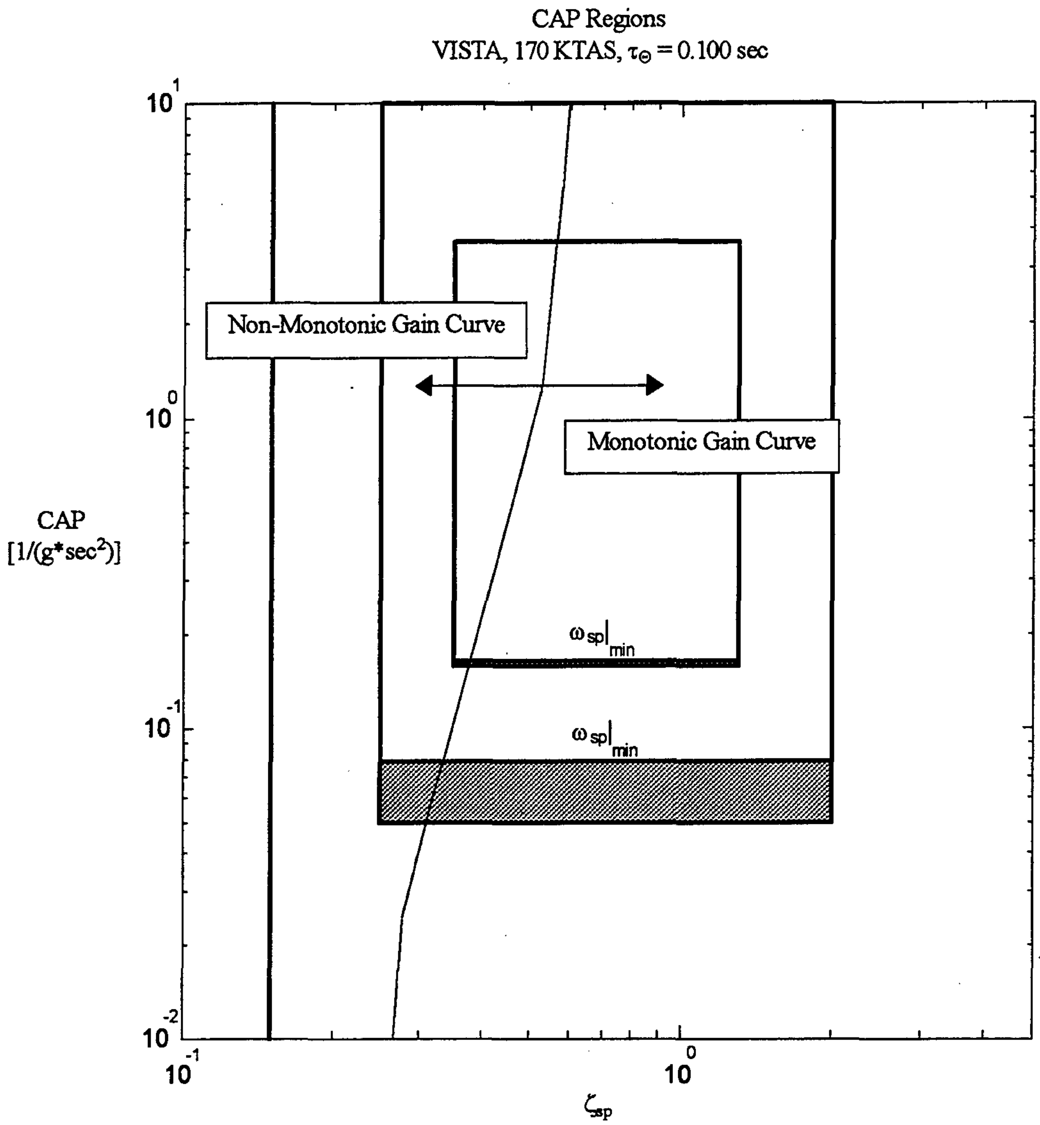


Figure 11 Non-Monotonic Type Bode Gain Curves in the CAP Space

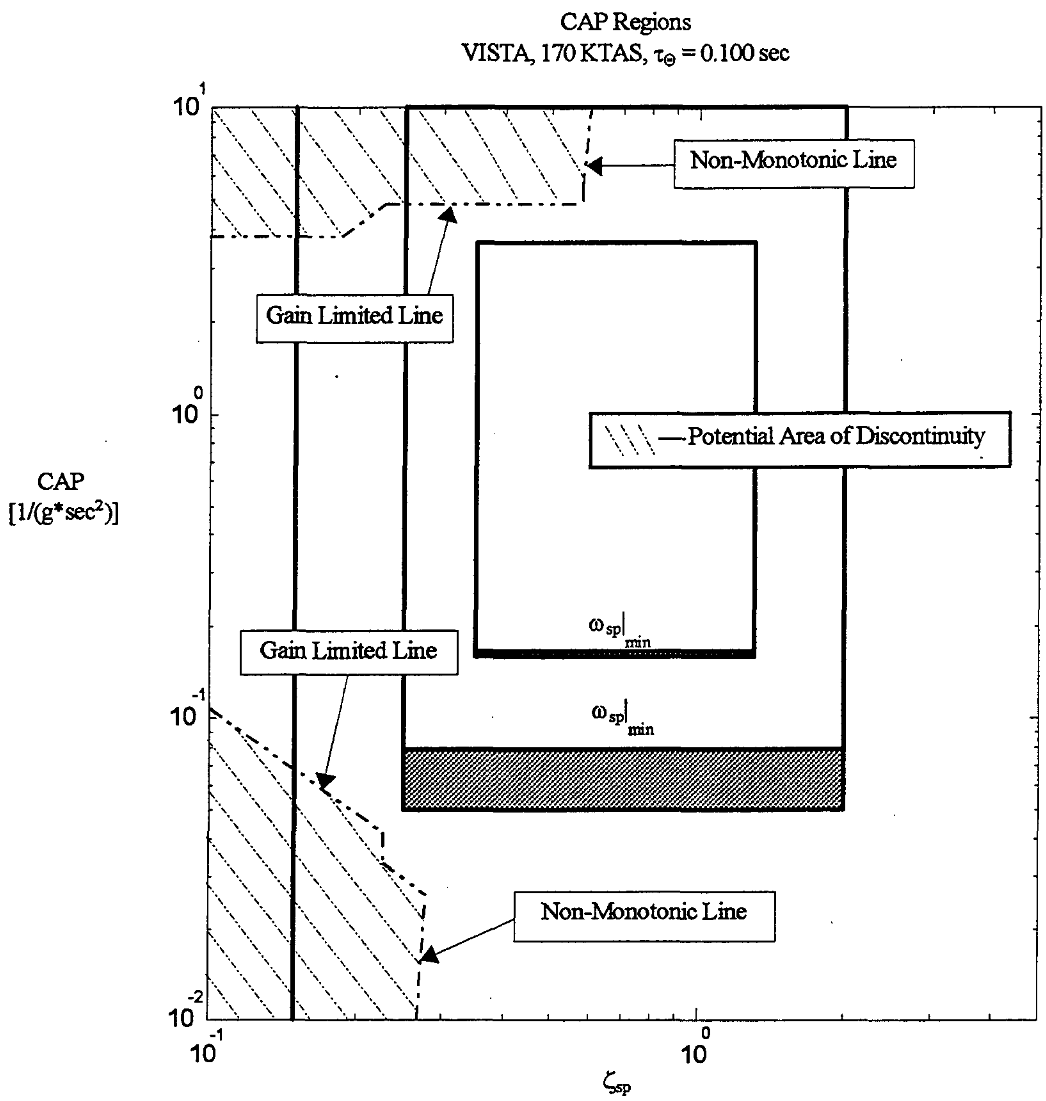


Figure 12 Potential Area of Bandwidth Discontinuity in the CAP Space

3.7 Jump Line

Figure 12 shows the regions in the CAP space where a potential existed for the bandwidth to have discontinuous jump. As stated before, within these regions the bandwidth was gain margin limited and the Bode magnitude curve was non-monotonic. The intersection of these two regions significantly reduced the area where a possible discontinuity could exist. However, this mapping did not identify the loci of points which defined the discontinuous jump line. The discontinuous jump line was characterized by ω_{BW_G} on the Bode plot jumping from the local peak near ω_{sp} to a lower ω_{BW_G} as a result of where the 6 dB gain line fell.

To locate the loci of points where a jump existed, insight was gained by looking at the definition of ω_{BW_G}. The gain limited bandwidth, ω_{BW_G}, was defined from Equations 9 and 12 which are reproduced below:

$$-\pi = \arctan\left(T_{\Theta_2}\omega_{180}\right) - \tau_{\Theta}\omega_{180} - \frac{\pi}{2} - \arctan\left(\frac{2\zeta_{sp}\omega_{sp}\omega_{180}}{\omega_{sp}^2 - \omega_{180}^2}\right) \tag{17}$$

$$\mathrm{lm}\left(\frac{\sqrt{\omega_{180}{}^2 + \left(1/T_{\Theta_2}\right)^2}}{\omega_{180}\sqrt{\left(\omega_{sp}^2 - \omega_{180}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{180}^2}}\right) + 6\,\mathrm{dB} = \mathrm{lm}\left(\frac{\sqrt{\omega_{BW_G}{}^2 + \left(1/T_{\Theta_2}\right)^2}}{\omega_{BW_G}\sqrt{\left(\omega_{sp}^2 - \omega_{BW_G}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{BW_G}^2}}\right). \tag{18}$$

Given a specific $1/T_{\Theta_2}$ and τ_{Θ}, ω_{BW_G} was a function of ζ_{sp} and ω_{sp}. This three dimensional surface defined ω_{BW_G} for all ζ_{sp} and ω_{sp}, showing the areas where jumps in ω_{BW_G} occurred.

Inspection of Equations 17 and 18 show that neither ω_{BW_G} nor ω_{180} could explicitly be solved for because of the non-linear, transcendental nature of the governing equations. However, ω_{BW_G} may be solved for numerically using various techniques. The technique used in this research was a modified version of Newton's method (25:454 - 464). For a detailed description on the method used, refer to Appendix E.

Figure 13 shows the non-linear behavior of the discontinuous jump. For example, examining the $\zeta_{sp} = 0.25$ line—corresponding to a vertical line in CAP—between a ω_{sp} of 1.0 and 2.5 rad/sec there was one solution for ω_{BW_G} until the tangency of the lower portion of the curve was reached. At the point of tangency there was two solutions for ω_{BW_G}. Between a ω_{sp} of 2.5 and 5.2 rad/sec there were three solutions for ω_{BW_G}. These three solutions corresponded to the three solutions pointed out in Chapter 2. There it was shown the line which defined ω_{BW_G} could either intersect the Bode magnitude curve at one, two or three locations. As stated in Chapter 2, the bandwidth with the highest ω_{BW_G} was chosen corresponding to the greater value of the ω_{BW_G} solutions on Figure 13. Once again, as ω_{sp} was increased just beyond 5.2 rad/sec the solution for ω_{BW_G} transitioned from two back to one solution. The discontinuous jump was defined by ω_{BW_G} "jumping" from a relatively large value to a relatively low value as ω_{sp} was increased as shown in Figure 13.

This method of determining ω_{BW_G} versus ω_{sp} was repeated for a wide range of ζ_{sp} resulting in Figure 14a. This figure shows the discrete jump in ω_{BW_G} versus ω_{sp} and ζ_{sp}. Figure 14b shows the discrete line when mapped onto a ω_{sp} versus ζ_{sp} range. This figure

was then easily converted onto the CAP space through use of Equation 2 as shown in Figure 15. The jump limit in Figure 15 was included to show that as ζ_{sp} was increased beyond a certain limit, there would be no jump in the bandwidth space.

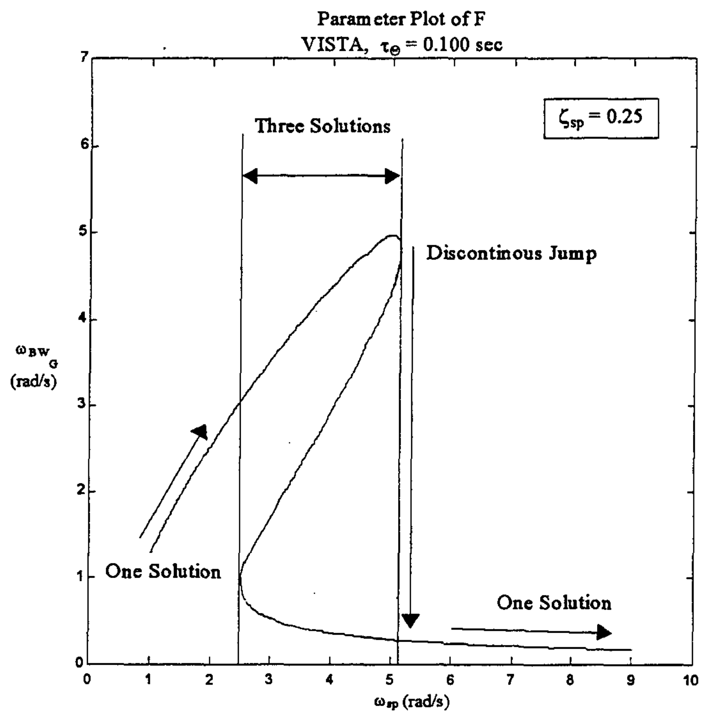
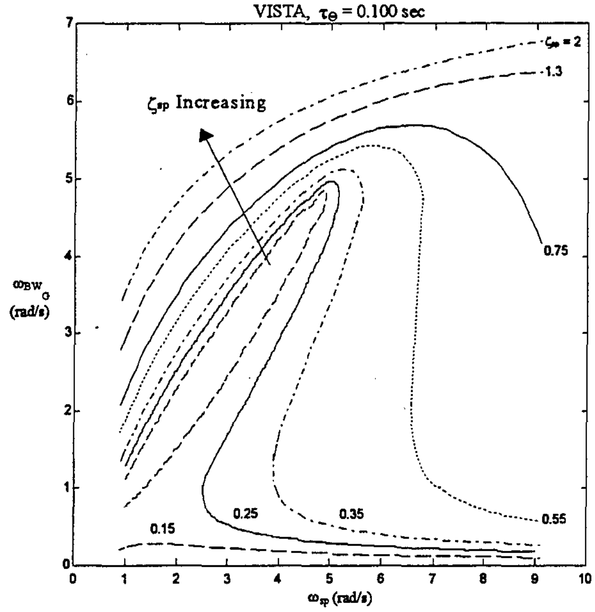
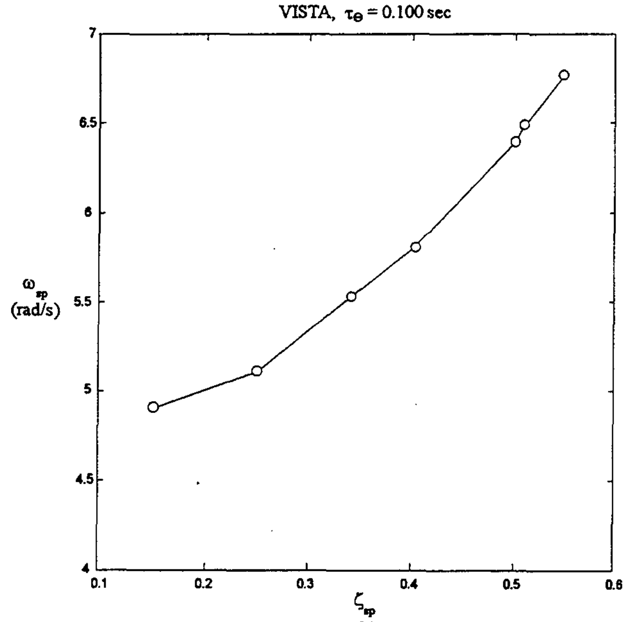


Figure 13 Discontinuous Jump Solution for $\zeta_{sp} = 0.25$



(a)



(b)

Figure 14 Composite Discontinuous Jump Solution

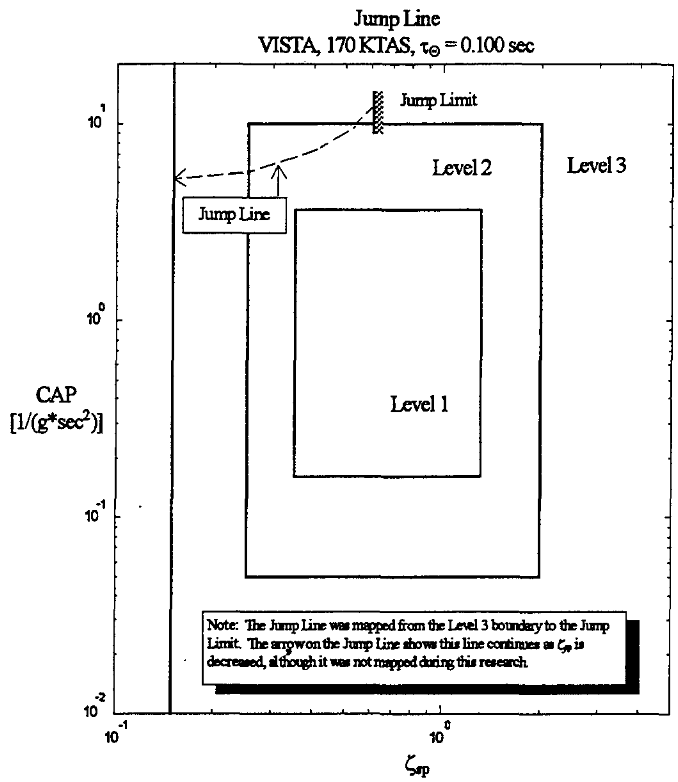


Figure 15 Jump Line Location in the CAP Space

Up to this point the $\omega_{sp}|_{min}$ and n/α limitations, excessive dropback area, gain and phase limited regions, non-monotonic gain curve and jump line have been developed and shown in the CAP space to aid in mapping CAP onto the bandwidth space. These regions are brought together in Figure 16 to show where they lay with respect to one another. With this knowledge it is now possible to map the CAP domain onto the bandwidth space. The results of this mapping are presented in Chapter 4.

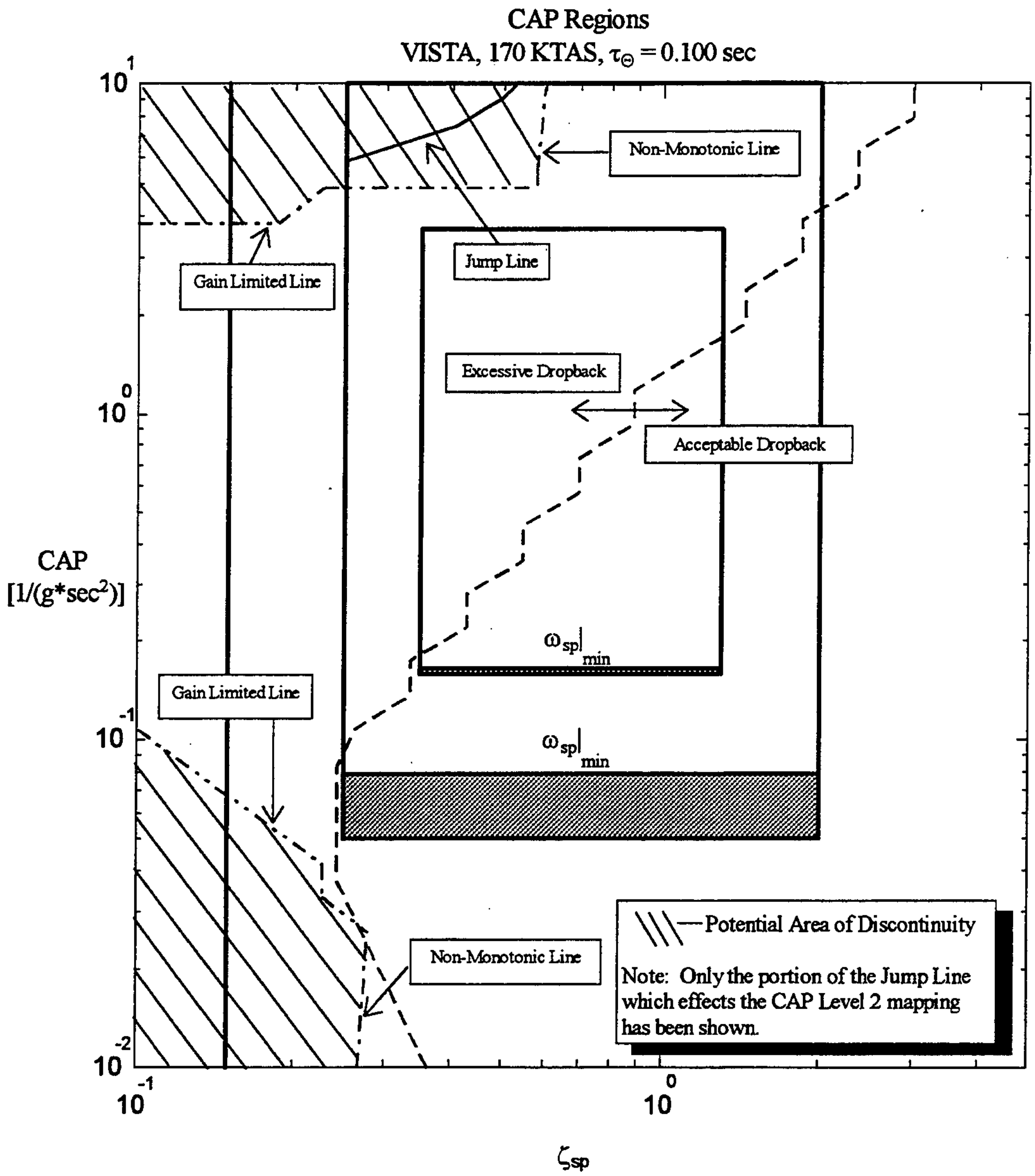


Figure 16 Composite View of the CAP Space

IV. Mapping Results

Chapter 3 developed and presented various regions within the CAP space. Chapter 4 presents the results of mapping CAP Level 1 and 2 onto the bandwidth space. The reason for this presentation order was so the reader would have a clear understanding of each individual region in the CAP space first. With this knowledge, it is now possible to understand the peculiarities of mapping CAP Level 1 and 2 onto the bandwidth space. This chapter only presents the mapping results for VISTA since this was the airframe used in Phase II of this research. The mappings for the Learjet type aircraft are similar to that of VISTA and are presented in Appendix B.

To determine the intersection of the CAP, bandwidth, and bandwidth with dropback criteria, the CAP domain was mapped onto the bandwidth criterion as described in Chapter 3. The variables K_Θ, $1/T_{\Theta_2}$ and τ_Θ were specified making Equation 4 unique—ω_{sp} and ζ_{sp} were specified due to the location in the CAP domain using Equation 2. Due to the definitions of bandwidth and dropback, K_Θ was independent of bandwidth and dropback. Thus K_Θ did not influence the solution. The variables $1/T_{\Theta_2}$ and τ_Θ were selected as nominal values for VISTA as presented in Table 3. With these nominal values the pitch attitude transfer function, Equation 4, was unique for each point in the CAP domain. Thus, each specific point in CAP defined a point in the bandwidth and dropback spaces.

4.1 CAP Level 1 Mapped onto the Bandwidth Space

The CAP Level 1, as specified by points A, B, C, and D in Figure 17, mapped onto the bandwidth space as shown in Figure 18 and the bandwidth space augmented by the dropback criterion as shown in Figure 19. Note the scale in Figure 18 was magnified to show the area of interest as related to Figure 5. The vertical lines are those lines which delineate bandwidth Level 1, 2 and 3. The shaded regions show the area where the CAP and bandwidth criteria agree.

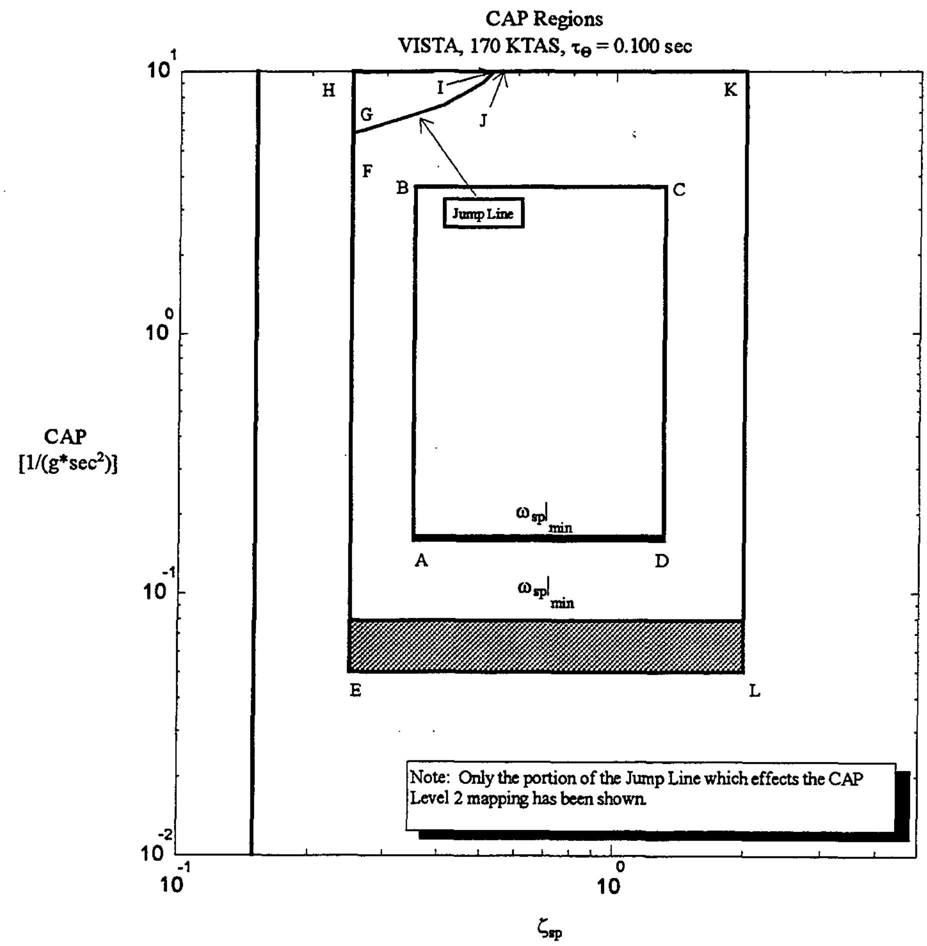


Figure 17 Area Map of CAP

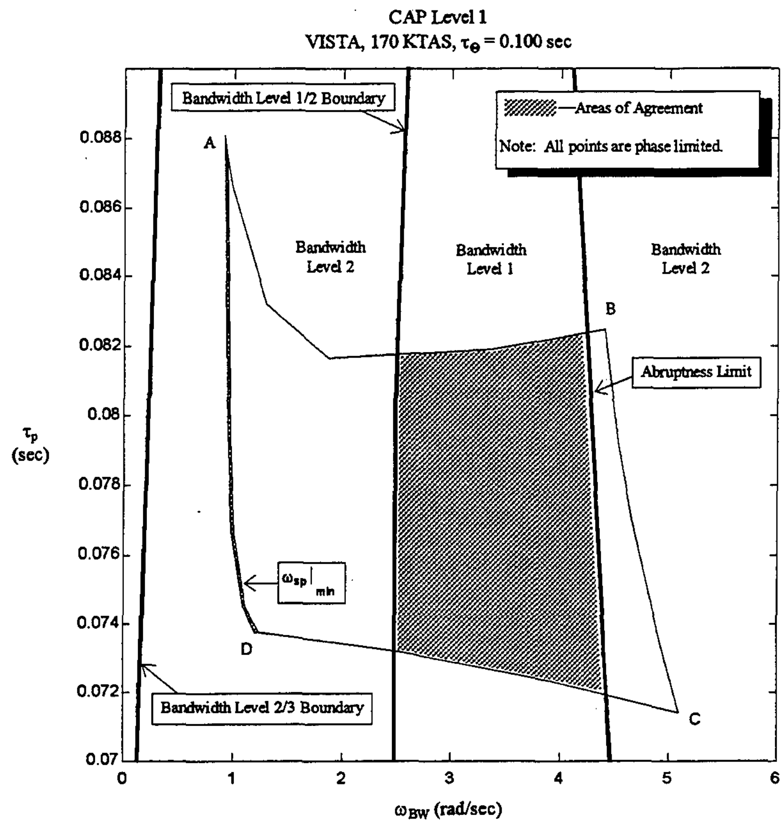


Figure 18 CAP Level 1 Mapped onto the Bandwidth Criterion

Figure 19 shows the same magnification as Figure 18. However, in this figure the proposed bandwidth boundaries are used along with application of the dropback criterion. Comparing Figure 18 to Figure 19 revealed that application of the dropback definition significantly decreased the area where CAP Level 1 agreed with the bandwidth criterion. This was supported by flight test results as will be shown in the flight test chapters. Note that in both Figure 18 and Figure 19, all CAP Level 1 points were phase limited as defined by the bandwidth criterion.

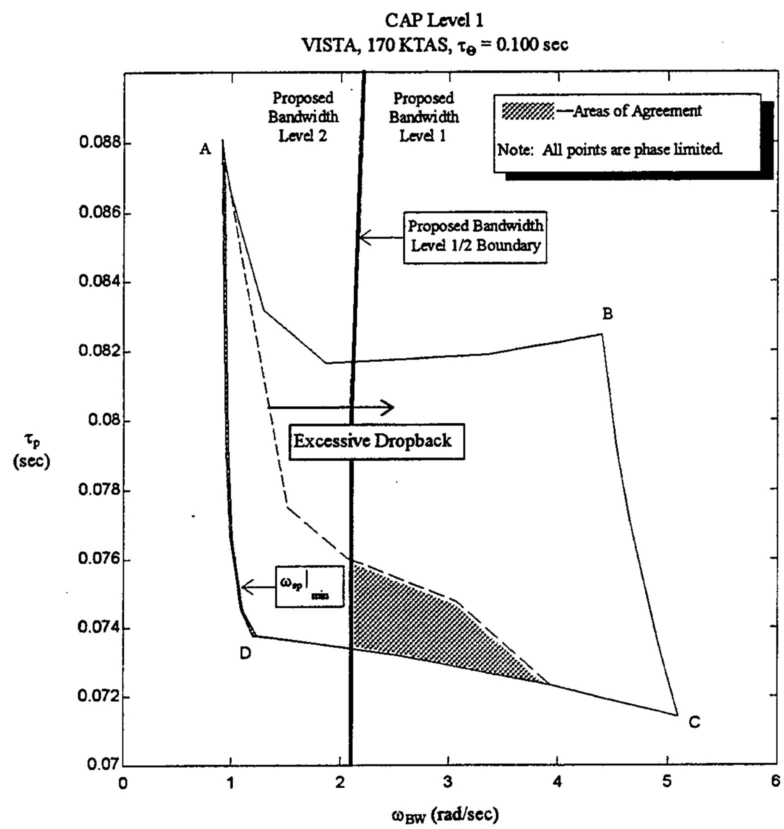


Figure 19 CAP Level 1 Mapped onto the Proposed Bandwidth with Dropback Criterion

4.2 CAP Level 2 Mapped onto the Bandwidth Space

Mapping CAP Level 2 onto the bandwidth space was not as straight forward as that for CAP Level 1. Due to the definition of bandwidth, the non-linear jump line was encountered when mapping CAP Level 2. As a result of the jump line, the closed CAP region EFJKLE shown in Figure 17 mapped onto the respective closed region in bandwidth shown in Figure 20. Note, the $\omega_{sp}|_{min}$ line in Figure 20 corresponds to the $\omega_{sp}|_{min}$ line in CAP as defined from MIL-STD-1797A. Similarly, the closed CAP region GHIG

mapped onto the respective closed region in bandwidth shown in Figure 21. However, mapping across the jump line resulted in an open region in the bandwidth space. For instance, the closed CAP region FHJF mapped onto an open region in bandwidth which contained a discontinuous jump.

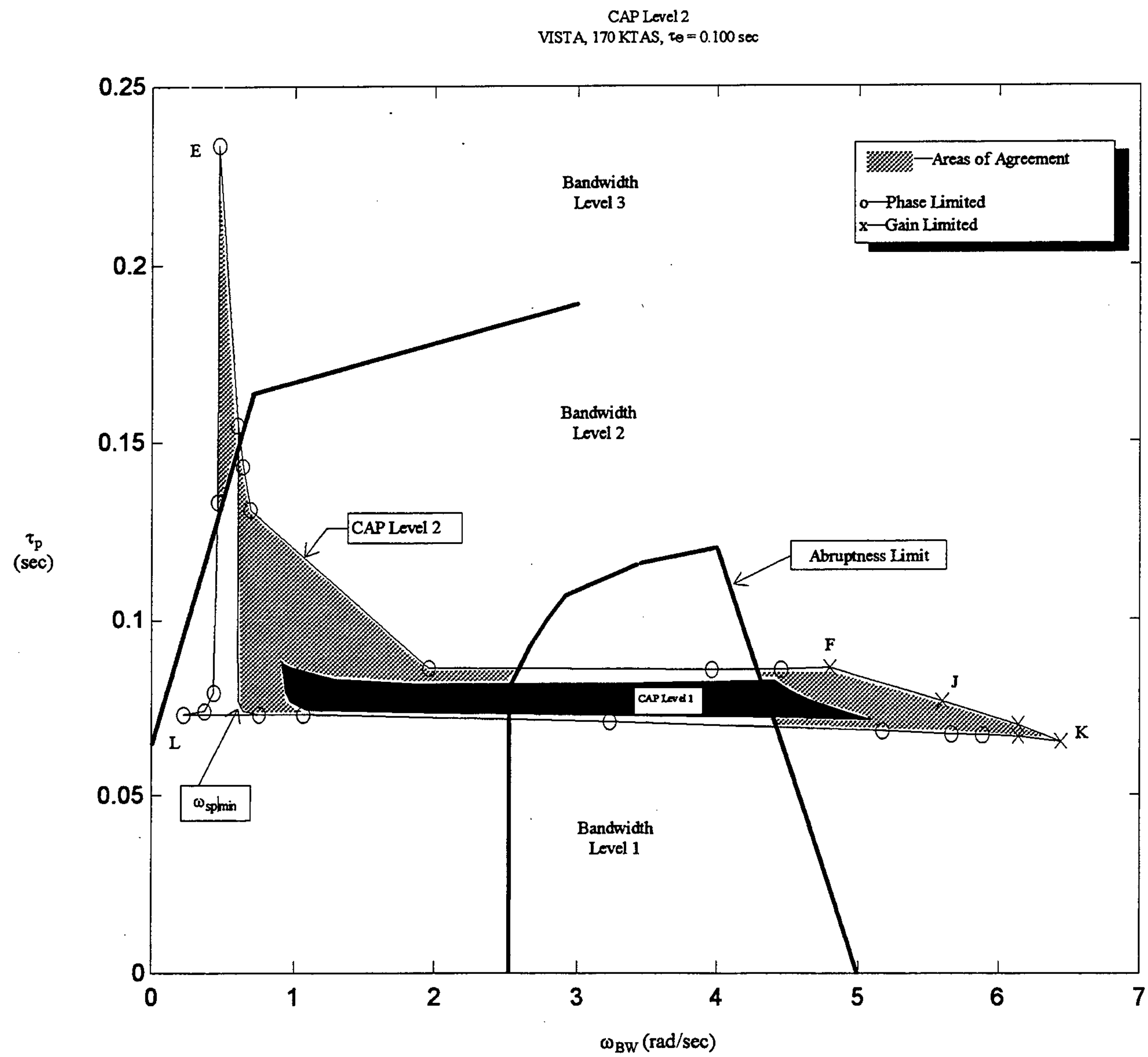


Figure 20 CAP Level 2 Mapped onto the Bandwidth Criterion

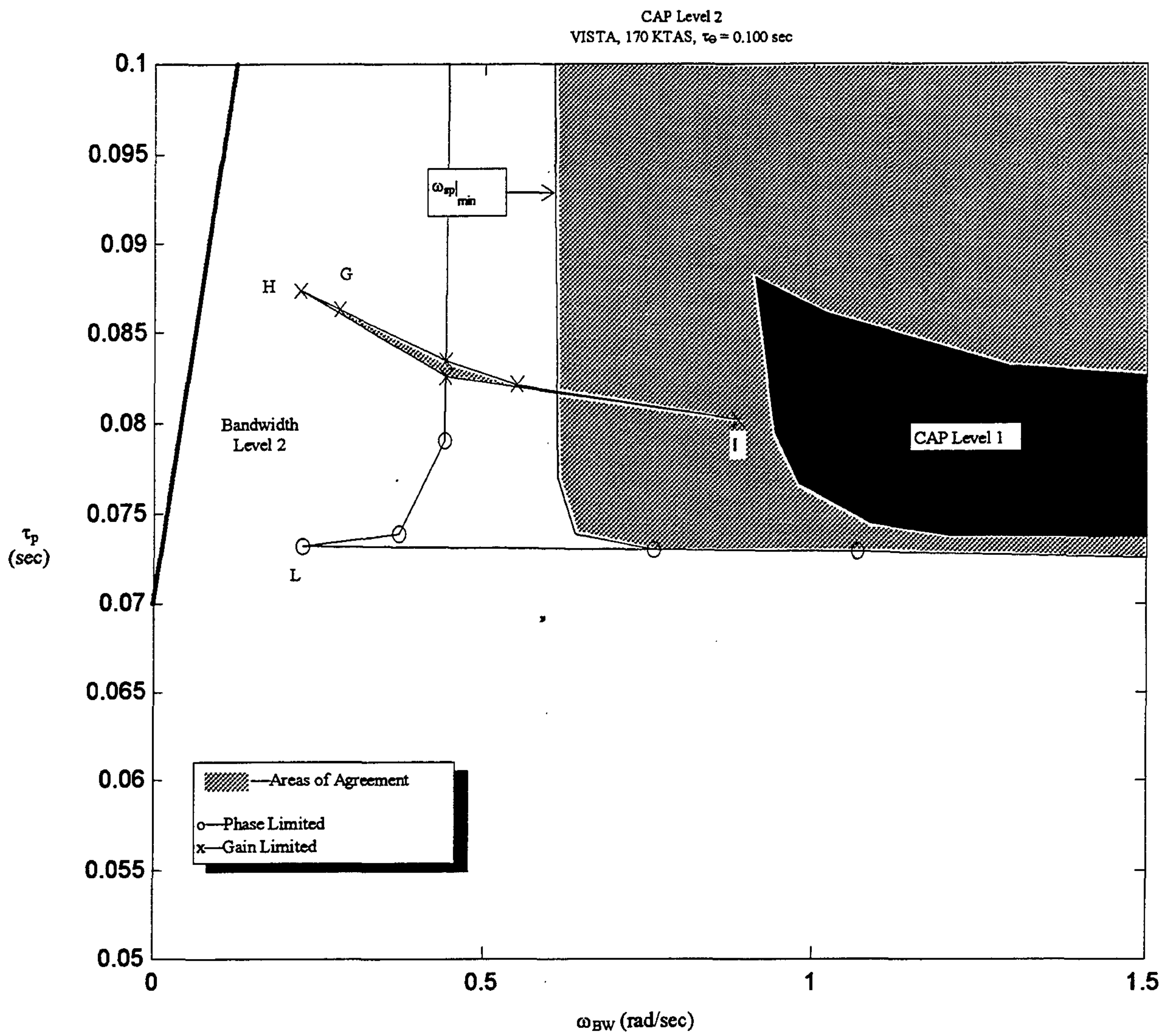


Figure 21 CAP Level 2 Mapped onto the Bandwidth Criterion—Jump Area

Mapping CAP Level 2 onto the proposed bandwidth space using the dropback criterion resulted in Figure 22 and Figure 23. Once again, including the dropback criterion changed not only the handling qualities boundaries but also those areas where the criteria agreed with one another. As shown in Figure 20 and Figure 22, application of the

dropback criterion and proposed boundaries resulted in the same areas of agreement as the bandwidth criterion for high bandwidths. Above approximately a bandwidth of 5 rad/sec, the dropback criterion increased the bandwidth to a Level 2 while the "Abruptness Limit" did the same resulting in agreement with CAP.

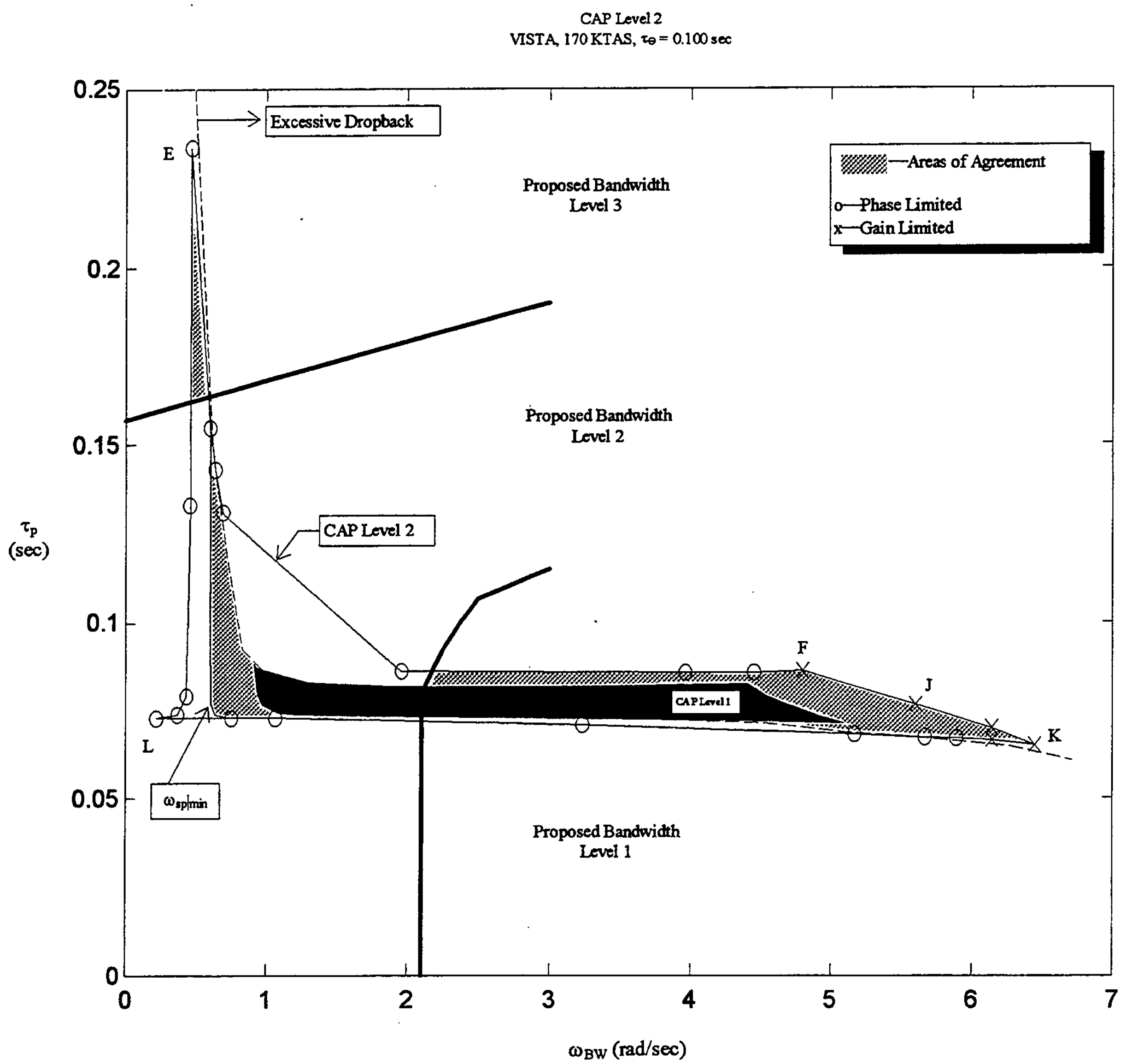


Figure 22 CAP Level 2 Mapped onto the Proposed Bandwidth with Dropback Criterion

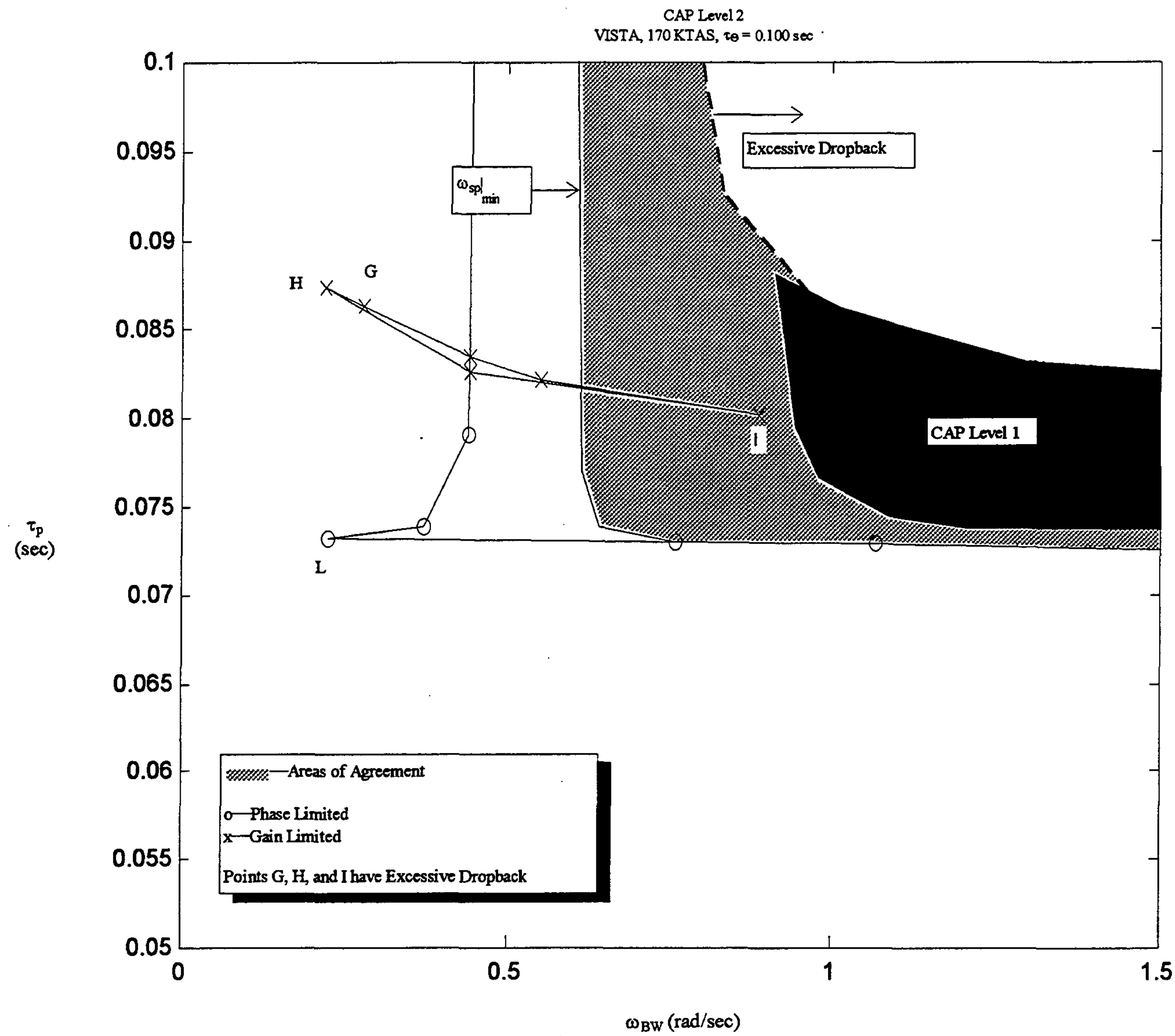


Figure 23 CAP Level 2 Mapped onto the Proposed Bandwidth with Dropback Criterion—Jump Area

Above a bandwidth of 2.2 rad/sec, the dropback criterion along with the proposed boundaries increased the area of agreement between the CAP and bandwidth criteria. As shown in Figure 20, for aircraft which lay above the CAP Level 1 region in the bandwidth

space and between a bandwidth of 2.5 and 4.5 rad/sec, the bandwidth criterion alone predicted a Level 1 aircraft while CAP predicted a Level 2 aircraft. Applying the dropback criterion to the proposed bandwidth space, as shown in Figure 22, resulted in both criteria predicting a Level 2 aircraft. Those aircraft which lay below the CAP Level 1 region with a bandwidth between the Level 1 boundary and 4.5 rad/sec were predicted to have Level 1 handling qualities by both the bandwidth and proposed bandwidth with dropback criteria while CAP predicted Level 2 handling qualities. The dropback criterion along with the proposed boundaries decreased the area of agreement below a bandwidth of 2.2 rad/sec as shown in Figure 22.

The region bounded by points GHIG mapped onto the closed area shown in Figure 21 and Figure 23. Using bandwidth alone resulted in both CAP and bandwidth predicting a Level 2 aircraft shown in Figure 21. Using the proposed bandwidth with dropback criterion resulted in a bandwidth Level 3 aircraft and a CAP Level 2 aircraft shown in Figure 23. Note points G, H, and I had excessive dropback even though they lay to the left of the excessive dropback line in the bandwidth space.

These results show the CAP domain mapped onto the bandwidth and proposed bandwidth with dropback criteria. Using these results, a flight test was completed using VISTA to simulate aircraft throughout the various criteria to obtain pilot opinion in those areas of agreement and conflict. Phase II of this research effort is presented in the following chapters.

V. Flight Test Description

Chapters 1 through 4 laid the ground work for the flight test phase of this research effort. This chapter will discuss the overall flight test setup, methods, conditions and techniques. The information contained herein is the precursor to Chapter 6, *Flight Test Results*. These two chapters present the reader with enough information from the flight test portion to draw conclusions between Phases I and II. However, the reader is encouraged to reference the published flight test report AFFTC-TR-95-78 for a more in-depth discussion of the flight test [27].

5.1 General

The NF-16D Variable-Stability In-Flight Simulator Test Aircraft (VISTA) was used in this flight test because of the range of dynamic parameters it was capable of simulating. It was a USAF test aircraft owned by the Flight Dynamics Directorate of Wright Laboratory, Wright-Patterson AFB, Ohio and operated by the Flight Research Department of Calspan Advanced Technology Center. Ten different variable stability system (VSS) configurations with a broad range of short period dynamics were evaluated during a high-gain lateral offset landing task. Each specific short period natural frequency and damping ratio combination was referred to as a VSS configuration.

Figure 24 presents the locations of the VSS configurations on the CAP space. The symbol "o" illustrates the desired location of the configuration. These locations were specifically chosen for their location with respect to the dropback line, jump line, and areas

of agreement and disagreement. The symbol "x" illustrates the actual location of the configurations as determined from flight test results. Calspan determined these flight test locations through a LOES match keeping $1/T_{\Theta_2}$ fixed at 0.455. The matches were assumed valid if they fell within the bounds specified by MIL-STD-1797A and were used to obtain the short period natural frequencies and damping ratios. The value of CAP was calculated using Equation 2 at an airspeed of 170 KTAS. For more information regarding the LOES match, refer to Section 5.4.1.

As seen in Figure 24, all VSS configurations generally moved up and to the left from the requested location. The main reason for this was VISTA contained an extra frame of time delay which was not accounted for when Calspan programmed the VSS configurations into the VSS system. However, this was accounted for in all post flight data reduction.

As a result of the VSS configurations' migration, configurations G, H, K, and P moved from the requested region of acceptable dropback to the region of excessive dropback. As the dropback definition required, dropback was measured from the actual aircraft response and not from the LOES response. As a result, all VSS configurations exhibited more dropback than the LOES predicted because of VISTA's phugoid mode effects. This was more pronounced for the lower frequency points J, K, and P where the short period natural frequency was closer to the phugoid natural frequency.

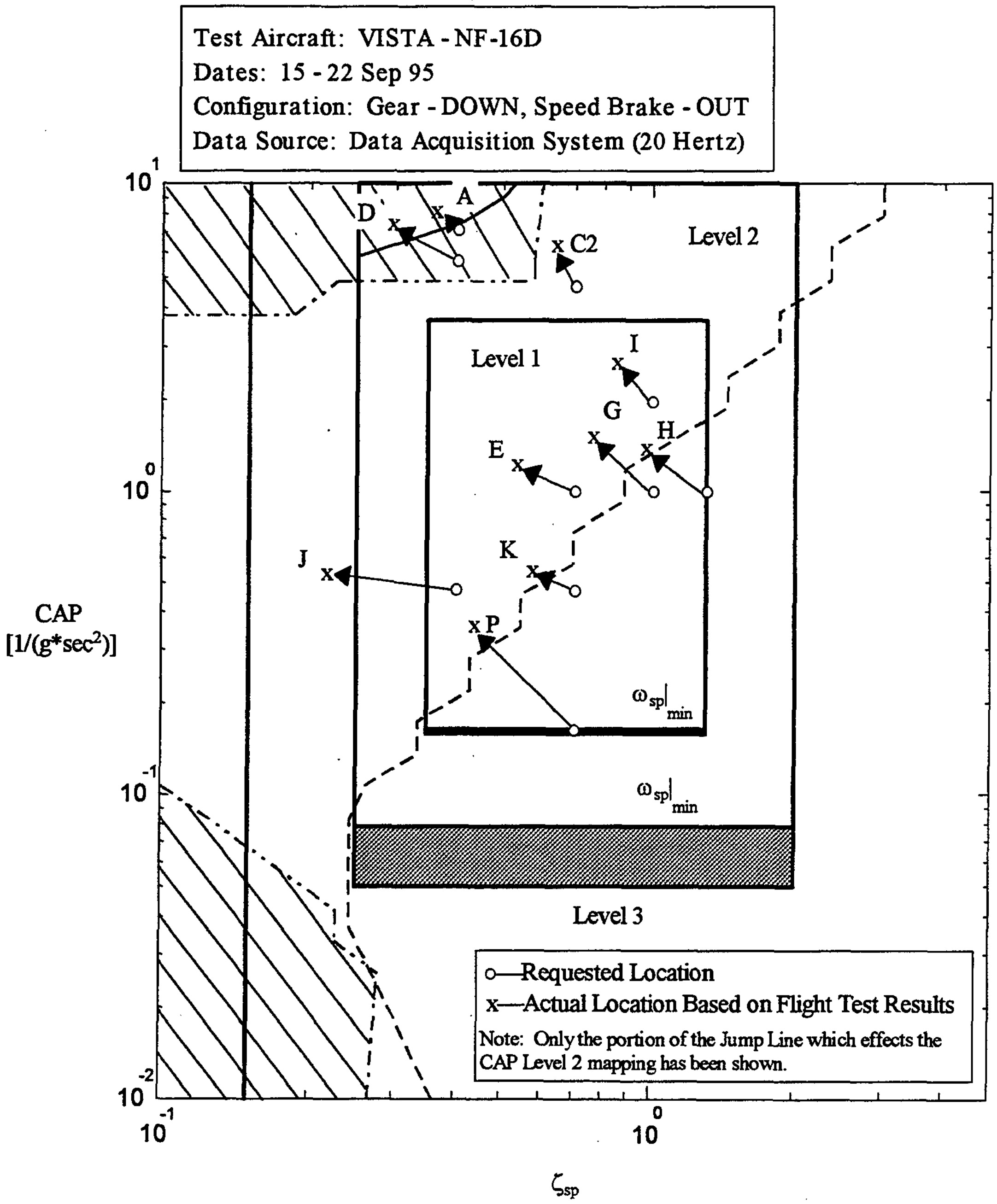


Figure 24 Location of Requested and Actual VSS Configurations on the CAP Space

Also from Figure 24, VSS configurations A and D lay above the jump line. Thus their LOES's bandwidths have jumped from a high frequency to a low frequency. The bandwidth criterion required using the aircraft's actual flight test Bode plot and not the LOES's Bode plot. As a result, the actual Bode plots did not show the characteristic jumps as predicted by the LOES due to VISTA's higher order dynamics. However, configurations A and D lay in the potential area of the jump discontinuity which was predicted to be a region of worsening handling qualities as presented in Chapter 3. In contrast, VSS configuration C2 lay outside this region. Thus pilot opinion trends were obtained through the potential area of the jump discontinuity.

One VSS configuration, located at $\zeta_{sp} = 0.4$ and CAP = $10/g{*}sec^2$, was requested to ensure a configuration had a low bandwidth due to the jump condition. However, this VSS configuration could not be simulated by VISTA due to the automatic safety trips disengaging the VSS. Thus, there was no configuration which had a low bandwidth due to the jump condition.

Figure 25 presents the actual VSS configurations on the bandwidth space as determined from flight test results. Again, these locations where determined from the configurations' actual flight test Bode plots. As seen, VSS configurations A and D had relatively large bandwidths as opposed to small bandwidths predicted by the LOES.

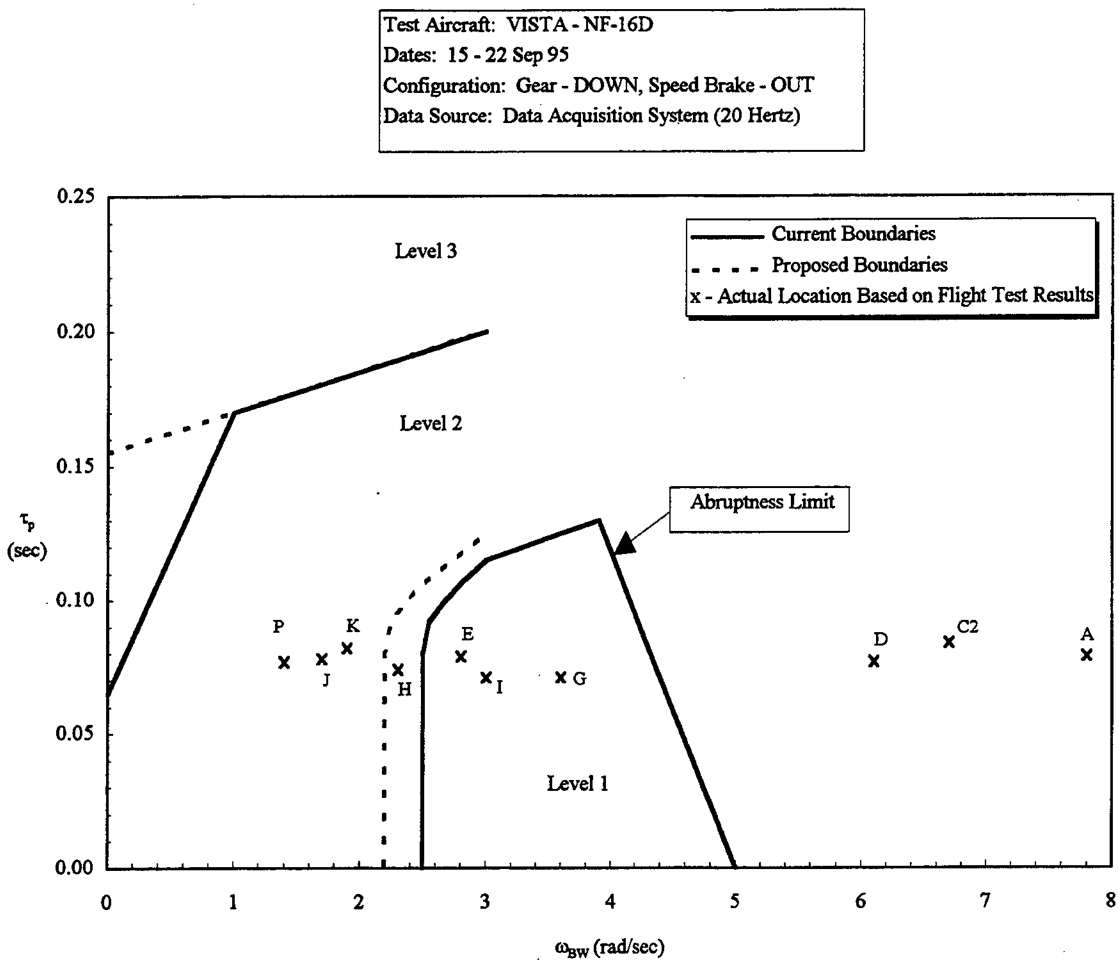


Figure 25 Location of VSS Configurations on the Bandwidth Space

Four test pilots of varying backgrounds were used for a wide range of pilot experience. Table 6 details the evaluation pilots' flying backgrounds. The four evaluation pilots rated the VSS configurations using the Cooper-Harper and pilot induced oscillation (PIO) rating scales during high-gain lateral offset landing tasks. Appendix A contains each of these rating scales.

Table 6 Evaluation Pilot Flying Experience

Evaluation Pilot	Weapon System Experience
1	C-141B
2	GR-7 (Royal Air Force Harrier)
3	B-1B, B-52G/H, T-38A
4	U-2R, T-38A, T-37

The Cooper-Harper rating scale, widely accepted in the handling qualities community, was used to judge aircraft performance and pilot workload. "Performance is the precision of aircraft control attained by the pilot. Workload is the amount of effort and attention, physical and mental, the test pilot must provide to attain that level of performance" (28:C-1). This rating scale requires the test pilot to answer questions starting in the lower left corner and eventually assigns a pilot rating due to the answers.

The PIO rating scale again has the test pilot answer questions about the aircraft's behavior starting in the lower left corner of the scale. Depending on the answers, a PIO rating is assigned. This scale "retains the important divisions between low and high gain tasks as well as between true oscillations and simple undesirable motions" (28:C-7). Where the Cooper-Harper scale clearly relates to the handling qualities levels defined in MIL-STD-1797A, the PIO rating scale is used more as a communication link helping to describe the type of motion encountered (28:C-8).

Frequency sweeps and pitch boxcar responses were flown defining and validating the VSS configurations' short period dynamics. The frequency sweeps were flown determining the configuration's actual pitch attitude Bode plot. This in turn was used for the LOES match and to determine the bandwidth and phase delay. The flight test pitch boxcar responses determined the dropback criterion for that configuration. The procedures for the frequency sweeps and boxcar inputs are described in detail in Sections 5.4.1 and 5.4.2.

Qualitative pilot opinion was gathered after each lateral offset maneuver. Included in these comments were weather effects such as winds and turbulence, with turbulence rated using the standard light, moderate and severe descriptors. Comments also included firmness of touchdown using soft, medium and firm descriptors.

For some VSS configurations, handling qualities during tracking (HQDT) and pitch capture tasks were flown before attempting to land those configurations. In this buildup approach all VSS configurations with predicted Level 3 handling qualities underwent an initial evaluation composed of HQDT and pitch capture tasks at approximately 10,000 feet pressure altitude. Additional VSS configurations with predicted Level 1 and 2 handling qualities were included in these buildups to maintain the aspect of blind testing by the evaluation pilots. Once the initial evaluation was accomplished for a particular VSS configuration, the determination as to whether landings should be attempted for predicted Level 3 VSS configurations was made.

During all of the flight tests, VISTA was configured with landing gear down and speedbrakes extended, at an on-speed angle of attack (AOA) of 11 degrees. This setup was required to set the initial conditions in the variable stability system at the proper n/α.

Prior to the actual evaluations, the evaluation pilots flew the landing task in a variety of different aircraft to familiarize them with the task over a broad range of aircraft handling qualities. The practice aircraft included the F-15, F-16, C-18, and T-38.

5.2 Test Item Description

5.2.1 General Aircraft Description

The project testbed was the NF-16D Variable-Stability In-Flight Simulator Test Aircraft (VISTA), USAF serial number 86-0048. It was a USAF test aircraft owned by the Flight Dynamics Directorate of Wright Laboratory, Wright-Patterson AFB, Ohio and operated by the Flight Research Department of Calspan Advanced Technology Center. The aircraft was a highly modified Block 30 Peace Marble II variant of a two-seat F-16. Pilot in command controls were moved from the front cockpit to the rear cockpit. The front cockpit had both a center and side stick with variable-feel. The front cockpit center control stick and rudder pedals were used by the evaluation pilot to provide inputs to a programmable flight control and VSS. The aircraft's basic empty weight (aircraft weight excluding usable fuel) was 21,750 pounds.

The aircraft had a dorsal fairing, heavyweight landing gear, an F110-GE-100 engine, and Block 40 avionics. Modifications to the aircraft included the additions of a

production digital flight control system (DFLCS), instrumentation/data acquisition system, and VSS interface. Items removed from the production aircraft included the 20 millimeter gun, ammunition drum, radar warning system, chaff/flare dispenser, nuclear weapon capability, advanced medium-range air-to-air missile (AMRAAM) capability, and expanded envelope gun sight. The layout of major components added to the VISTA are described in Appendix C.

5.2.2 Test Item Instrumentation

The VISTA was equipped with an Ampex AR700 airborne digital data recorder. Two hundred channels of data were recorded at 100 samples per second with twelve bit resolution. An additional 60 analog VSS parameters were also recorded. The VISTA was equipped with two videocassette (VHS) video recorders, capable of recording the Head-up Display (HUD) and Multi-function Display (MFD).

5.2.3 The Variable Stability System

The VISTA's flight control system simulated a classical second order response for the different VSS configurations. To achieve the desired VSS configurations, VISTA used angle of attack, pitch angle, pitch rate, and velocity feedback loops. The angle of attack and pitch rate feedback loops were used to achieve the desired short period dynamic characteristics. The pitch angle and velocity feedback loops were used to decrease the influence of the phugoid mode. To simulate each configuration, the VSS

provided computer-controlled commands to the horizontal tails, rudder, flaperons and engine.

In the event of a problem with the VSS flight controls or its handling qualities, the rear seat safety pilot was able to disengage the front seat stick and throttle. In addition to manual disengages by either pilot, the VISTA control system contained over 100 automatic trips. These safety monitors protected the aircraft from excessive loads, sensor or computer failures, and structural excitation.

The following aircraft dynamic models were used during all flight tests. They were provided by the Calspan Corporation and were not validated by the flight test team. These dynamic characteristics were optimized by Calspan to provide good flight control harmony over the wide range of short period dynamics. These models were held constant to facilitate consistency and repeatability for the full range of short period dynamics evaluated. It was recognized that these characteristics may not have provided the optimum control harmony for every VSS configuration tested.

5.2.3.1 Aircraft Phugoid Model

The VISTA's phugoid characteristics had a natural frequency of 0.023 radians per second, damping ratio of 0.2 and $1/T_{\theta_1}$ of 40 radians per second.

5.2.3.2 Aircraft Lateral-Directional Model

The VISTA's lateral-directional characteristics were a Dutch roll natural frequency of 1.94 radians per second and damping ratio of 0.24, and a roll mode time constant of 0.55 second with a time delay of 0.14 second. This time delay was determined from the

"maximum roll acceleration to half the input time history" method. The steady-state roll rate to roll controller force was 6.5 degrees per second per pound.

5.2.3.3 Stick Dynamics

The longitudinal center stick force gradient was 15 pounds per inch, while the lateral stick force gradient was 10 pounds per inch. The longitudinal stick deflection, δ_{es}, to stick force, F_{es}, transfer function was:

$$\frac{\delta_{es}}{F_{es}} = \frac{30^2}{15(s^2 + 2(0.7)(30)s + 30^2)}. \tag{33}$$

The lateral stick deflection, δ_{as}, to stick force, F_{as}, transfer function was:

$$\frac{\delta_{as}}{F_{as}} = \frac{30^2}{10(s^2 + 2(0.7)(30)s + 30^2)}. \tag{34}$$

As seen from Equations 33 and 34, the center stick's damping ratio was 0.7 while the natural frequency was 30 radians per second.

5.2.3.4 Actuator Dynamics

The VISTA's longitudinal actuator transfer function was:

$$\frac{\delta e_{pos}}{\delta e_{cmd}} = \frac{1.8862\text{x}10^7 \cdot (s^2 + 2(0.03)(97)s + 97^2)}{(s^2 + 2(1.18)(63.3)s + 63.3^2)(s^2 + 2(0.57)(70.7)s + 70.7^2)(s^2 + 2(0.03)(94.2)s + 94.2^2)}, \tag{35}$$

where $\delta_{e_{pos}}$ was the actual position of the actuator and $\delta_{e_{cmd}}$ was the commanded postion.

5.2.3.5 Sign Convention

Longitudinally, a positive pitch rate was defined by the rotation vector out the right wing resulting from a positive aft stick deflection and a negative horizontal stabilator deflection. Laterally, a positive roll rate was defined by the rotation vector out the nose resulting from a positive right stick deflection and positive aileron deflection. Directionally, a positive yaw rate was defined by the rotation vector through the bottom of the aircraft resulting from a positive rudder pedal deflection and a negative rudder deflection.

5.2.3.6 Ground Based Simulator Definitions

Calspan's ground based simulation of VISTA showed the aircraft's n/α varied with fuel weight. Table 7 shows $1/T_{\theta_2}$ and n/α for several fuel weights at 11° AOA in the approach and landing configuration (Gear - DOWN, Speedbrakes - OUT). The high frequency zero, $1/T_{\theta_2}$, was calculated from:

$$\frac{1}{T_{\theta_2}} \approx \frac{n}{\alpha} \cdot \frac{g}{V} \quad (36)$$

Table 7 Ground Based Simulator n/α at Different Fuel Weights
(11° AOA, Approach and Landing Configuration)

Fuel Weight (pounds)	True Airspeed (knots)	Calibrated Airspeed (knots)	n/α	$1/T_{\theta_2}$
8,092	180	167	4.0821	0.4370
6,050	173	161	4.2427	0.4550
4,522	169	157	4.3360	0.4650
3,570	166	154	4.4350	0.4757
2,000	161	149	4.5540	0.4880
952	159	147	4.7600	0.5100

5.3 Methods and Conditions

All VSS configurations were evaluated by Calspan in the ground simulation mode of VISTA prior to flight. Each VSS configuration was cleared by Calspan's safety pilots or USAF Test Pilot School staff pilots prior to being flown by the evaluation pilots. Clearing flights started with normal straight-in approaches and progressed to the lateral offset. Those points which were predicted to have Level 3 handling qualities by at least one of the prediction methods were evaluated during a HQDT task and a pitch capture task. Flight tests were limited to a maximum steady-state crosswind of 15 knots and a tailwind of 10 knots for safety and data quality considerations.

Each VSS configuration was flown at least three times by at least two different evaluation pilots. For each VSS configuration evaluated, the pilot performed at least three landings to quantitatively and qualitatively evaluate the handling qualities of that particular configuration. Offset landings were accomplished as described in Section 5.4, Test Procedures. Pilot comments were recorded during every evaluation and culminated in a single Cooper-Harper and PIO rating for each configuration. Ratings were assigned after the final landing attempt of that particular VSS configuration. These ratings were the pilots' overall evaluation taking into account the VSS configuration's performance and workload during the landing attempts.

The sorties were broken down with the intent of evenly distributing VSS configurations among the different pilots. This is to say, no single pilot ended up with all predicted handling qualities Level 3 VSS configurations, or conversely, all Level 1 VSS configurations. Rather, the attempt was made to evenly distribute VSS configurations among the pilots based principally on the predicted handling qualities of the various configurations. Further, during any particular sortie, only Calspan personnel, including the safety pilot, and the two project flight test engineers knew exactly which VSS configurations were being tested. Pilots were occasionally given the same test point without their knowledge to document their consistency.

5.4 Test Procedures

To ensure the VSS configurations flown had the proper dynamic characteristics, manual and programmed frequency sweeps and programmed pitch boxcar inputs were

flown. Frequency sweeps were used to obtain data for frequency response analysis (FRA) to determine the CAP and bandwidth criteria while time responses from the boxcar inputs were used to determine the dropback criterion.

5.4.1 Frequency Sweeps

Frequency sweeps were flown between 10,000 and 12,000 feet pressure altitude. They were flown both manually and using the VISTA's programmed test input (PTI). The frequency range of the sweeps was from approximately 1 to 10 radians per second. Data were recorded by the onboard data acquisition system (DAS) at a rate of 100 Hertz. The data were then reduced at a rate of 20 Hertz. Calspan provided the data from the DAS. A minimum of 1,024 data points were required for the frequency response analysis. The recorded data parameters used in this flight test are listed in Table 8. Parameters derived from flight test data are listed in Table 9.

The FRA was performed through ensemble averaging with a program developed at the USAF Test Pilot School using MATLAB®. Calspan took the resulting pitch rate to stick deflection Bode plots and performed a LOES match holding $1/T_{\Theta_2}$ fixed at 0.455 to identify the dynamic characteristics of each VSS configuration. The matches were assumed valid if they fell within the bounds specified by MIL-STD-1797A and were used to obtain the short period natural frequencies and damping ratios defining CAP and the equivalent time delay. The Bode plots were also used for the bandwidth analysis.

Table 8 DAS Parameters Recorded During Testing

Parameter
Longitudinal stick displacement
Longitudinal stick force
Lateral stick displacement
Lateral stick force
Stabilator position (L&R)
Flaperon position (L&R)
Barometric Altitude
Barometric Altitude rate
True Airspeed
Calibrated Airspeed
Angle of attack, α
Pitch angle, θ
Pitch rate, q
Normal Load Factor at Center of Gravity, n_z
Fuel weight

Table 9 Flight Test Data Parameters Derived from Post Flight Analysis

Parameter
n/α
T_{Θ_2}
Short Period Undamped Natural Frequency, ω_{sp}
Short Period Damping, ζ_{sp}
Lower Order Equivalent Time Delay, τ_{Θ}
Gain Bandwidth, ω_{BW_G}
Phase Bandwidth, ω_{BW_P}
Phase Delay, τ_p
Dropback, Drb

5.4.2 Boxcar Inputs

Time responses from the boxcar inputs were used to measure dropback. These inputs were generated using VISTA's PTI and were flown between 10,000 and 12,000 feet pressure altitude. The step input was applied until a steady-state pitch rate was obtained; the step input was then taken out. The data were collected with the onboard DAS at a sample rate of 100 Hertz and then downloaded to a personal computer at a rate of 20 Hertz. Recorded data parameters are detailed in Table 8.

5.4.3 Offset Landing Task

The offset landing task began at a 300 feet lateral offset at 300 feet above ground level (AGL). The task was to maneuver the aircraft landing softly in a predetermined landing zone. Pilots assigned one Cooper-Harper rating and one PIO rating to the task for each VSS configuration tested and made qualitative comments on the configurations' handling qualities. Each pilot performed the landing task at least three times for each assigned VSS configuration prior to assigning a single Cooper-Harper and PIO rating, while qualitative comments were gathered after each landing attempt. More than three landing attempts were flown per VSS configuration if the evaluation pilot required more landings to accurately assign the pilot ratings.

The VISTA was configured for the specific VSS configuration by the safety pilot on downwind. The test aircraft was established on final, approximately five miles from the threshold, offset 300 feet to the left of the runway centerline and configured for landing with gear down and speed brakes extended. When on-speed for an 11° AOA approach,

the VSS was engaged and the safety pilot transferred aircraft control to the evaluation pilot.

The evaluation pilot flew the instrument landing system's (ILS) glideslope down final, on speed while maintaining the 300 feet left offset. At 500 feet AGL, the front cockpit Head-Up Display (HUD) was dimmed so it was not visible to the evaluation pilot, preventing flight path marker (FPM) dynamics from influencing the task. The rear cockpit HUD display was still visible to the safety pilot. At 300 feet AGL, referenced by the radar altimeter, the safety pilot called "Maneuver." The offset task setup is shown below in Figure 26.

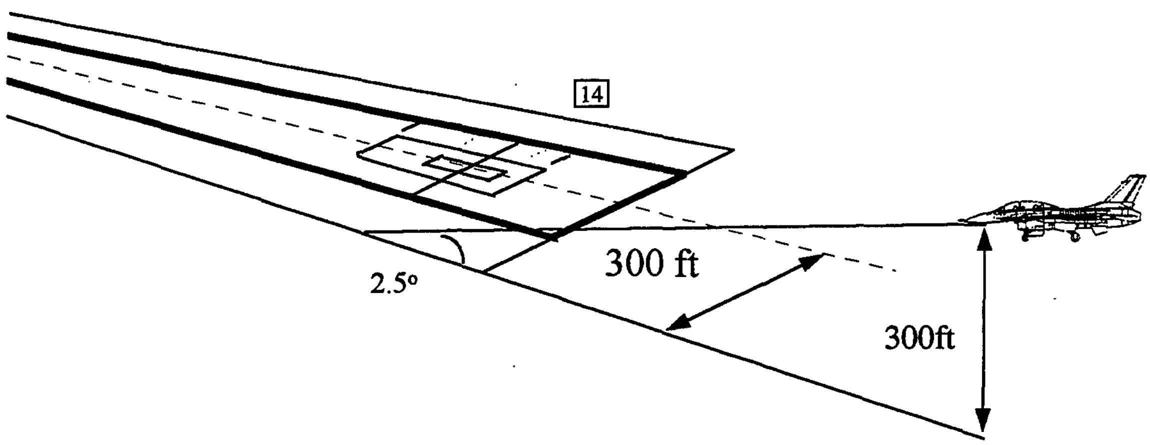


Figure 26 Lateral Offset Task Setup

At the safety pilot's "maneuver" call the evaluation pilot maneuvered to line up on the runway centerline and land in the touchdown zone box painted on the runway. The

pilot attempted to land in the center of the "desired" box, on speed and on AOA, with a minimal sink rate. If the maneuver appeared unsafe, either pilot could initiate a go-around. If the VSS tripped off, the safety pilot immediately took control of the aircraft.

5.4.4 Landing Zone

Specialized runway markings were painted on Runway 22 at Edwards AFB to delineate the desired and adequate touchdown zones. Standard 18-inch wide white paint lines were used for all markings. The desired landing zone was a 400 feet long by 25 feet wide box. The front of the desired zone was 800 feet down the runway. This placed the center of the desired zone 1,000 feet down the runway. The adequate landing zone was 1,000 feet long by 50 feet wide. The adequate zone was placed 600 feet down the runway. These distances also corresponded with the placement of the runway lights providing a backup in case the lines on the runway became obscured or otherwise unusable. The landing zone is shown in Figure 27.

5.4.5 Landing Task Evaluation

The evaluation pilot used touchdown point information, firmness of touchdown and workload to assign the Cooper-Harper and PIO ratings. The evaluation pilot received feedback on longitudinal touchdown position from ground observers over the very high frequency (VHF) radio. The evaluation pilot and safety pilot assessed the lateral touchdown position. For the landing to be considered in a zone, both main gear were required to be on or inside the respective line.

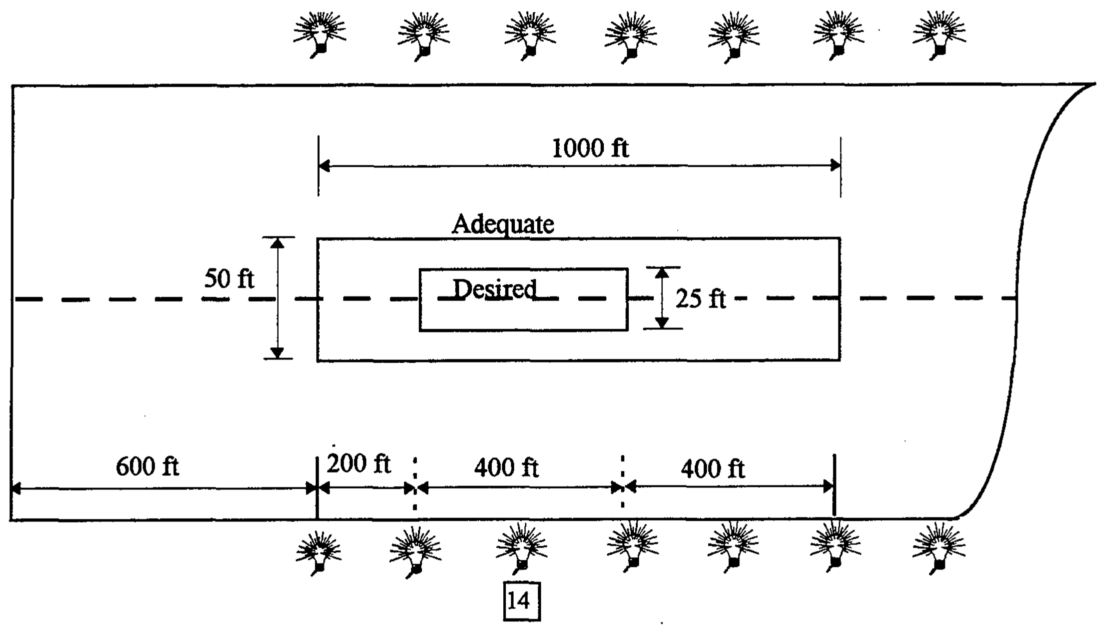


Figure 27 Landing Zone Markings and Dimensions

Both the safety and evaluation pilot qualitatively assessed the landing as either soft, medium or firm. Touchdown firmness was evaluated qualitatively and used in the Cooper-Harper rating. A soft landing was desired, medium was adequate, and firm was not adequate. A qualitative evaluation was used as no quantitative feedback was accurate or timely enough. Vertical velocity from the aircraft instruments was considered but determined to be inaccurate due to the lag in the system while the vertical acceleration or velocity from the DAS were not immediately available to the pilot. The same safety pilot flew on all test flights, providing consistency in landing firmness assessments between evaluation pilots.

Immediately after evaluating a VSS configuration, the test pilot combined the landing zone feedback, firmness of touchdown, and workload required to assign a Cooper-Harper and PIO rating. On downwind the safety pilot flew the aircraft while the evaluation pilot answered questions on the comment card to help evaluate the aircraft's handling qualities. The landing and pilot comments were recorded on the HUD video tape for post-flight analysis and data transcription. A camera on the ground near the approach end of the runway also recorded the aircraft from final through touchdown for post flight analysis. The onboard DAS recorded the time response data for each landing.

After each flight test mission, the evaluation pilot reviewed the HUD videotape and test card comments. All appropriate mission data was entered into the pilot comment computer database. The database contained pilot remarks for each VSS configuration flown, Cooper-Harper and PIO ratings, data parameters for each individual offset approach, and many other pertinent pieces of information. A complete summary of data recorded in the pilot comment database is contained in the flight test report [27].

This chapter has presented the flight test phase in detail. Chapter 6 will now present the results of the flight test.

VI. Flight Test Results

6.1 VSS Configuration Locations

Using the procedures set forth in Chapter 5, four test pilots quantitatively and qualitatively evaluated ten widely varying VSS configurations. A VSS configuration was defined as an unique combination of VISTA's second order short period damping ratio and frequency. These ten VSS configurations were specifically chosen for their placement within the CAP, bandwidth and dropback spaces. Figure 28 through Figure 30 show where the actual VSS configurations lay in the CAP, bandwidth and dropback spaces as determined from flight test results. Note that in Figure 29 the proposed bandwidth with dropback Level 1 boundary ends at 3 rad/sec. VSS configurations A, C2, D, and G were assumed to lay in the Level 1 region even though the boundary has not been defined at the higher bandwidth frequencies. Hoh concurred with this assessment since the dropback criterion was designed for these types of configurations [29].

Table 10 presents the ten VSS configurations evaluated during the flight test along with their defining short period lower order equivalent system (LOES) characteristics and predicted handling qualities. The high frequency zero, $1/T_{\theta_2}$, was fixed at 0.455 during the LOES match corresponding to an airspeed of 173 KTAS as shown in Table 7.

Flight test pilot ratings were then compared to each predictive metric. A summary of pilot comments for each VSS configuration follows in this chapter. For a more in-depth discussion refer to the flight test report, AFFTC-TR-95-78 [27].

Difficulty in measuring the dropback criterion from flight test results was encountered. It was not uncommon for the pitch attitude of VISTA to approach ±20 degrees during the boxcar input, especially for the low frequency configurations. The excessive pitch attitude caused difficulties in keeping the airspeed within tolerances. It was also difficult for the test pilots to determine when a steady-state pitch rate was reached in-flight. Much engineering judgment was used during data reduction when applying the definition due to these difficulties. Keep in mind that VISTA's computer controlled PTI's were used for the boxcar inputs. If these were flown manually it is predicted that much more dispersion would have resulted.

Table 10 Summary of Flight Test Results for Each VSS Configuration

VSS Configuration	Lower Order Equivalent System			CAP $[1/(g^*sec^2)]$	ω_{BW_G} (rad/sec)	ω_{BW_P} (rad/sec)	ω_{BW} (rad/sec)	τ_p (sec)
	ω_{sp} (rad/sec)	ζ_{sp}	τ_θ (sec)					
A	5.68	0.384	0.040	8.05	7.8	7.9	7.8	0.079
C2	4.97	0.632	0.075	6.16	6.7	6.8	6.7	0.084
D	5.40	0.290	0.080	7.27	6.1	6.1	6.1	0.077
E	2.18	0.523	0.072	1.19	3.8	2.8	2.8	0.079
G	2.50	0.785	0.078	1.56	5.2	3.6	3.6	0.071
H	2.29	0.967	0.070	1.31	2.3	3.8	2.3	0.074
I	3.28	0.830	0.085	2.68	3.0	5.1	3.0	0.071
J	1.44	0.214	0.066	0.52	2.1	1.7	1.7	0.078
K	1.44	0.555	0.066	0.52	3.2	1.9	1.9	0.082
P	1.20	0.435	0.066	0.36	2.4	1.4	1.4	0.077

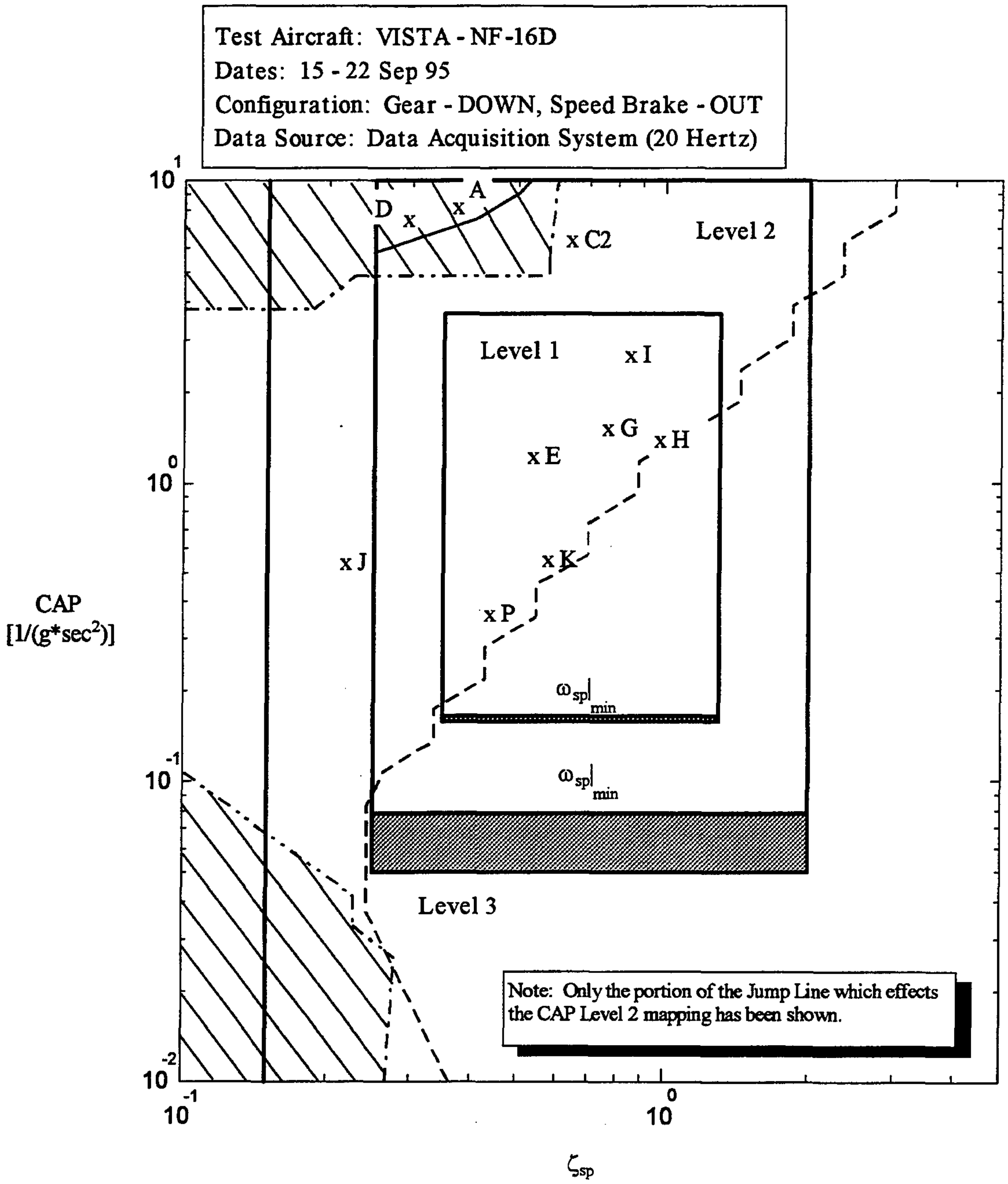


Figure 28 Location of VSS Configurations on the CAP Space

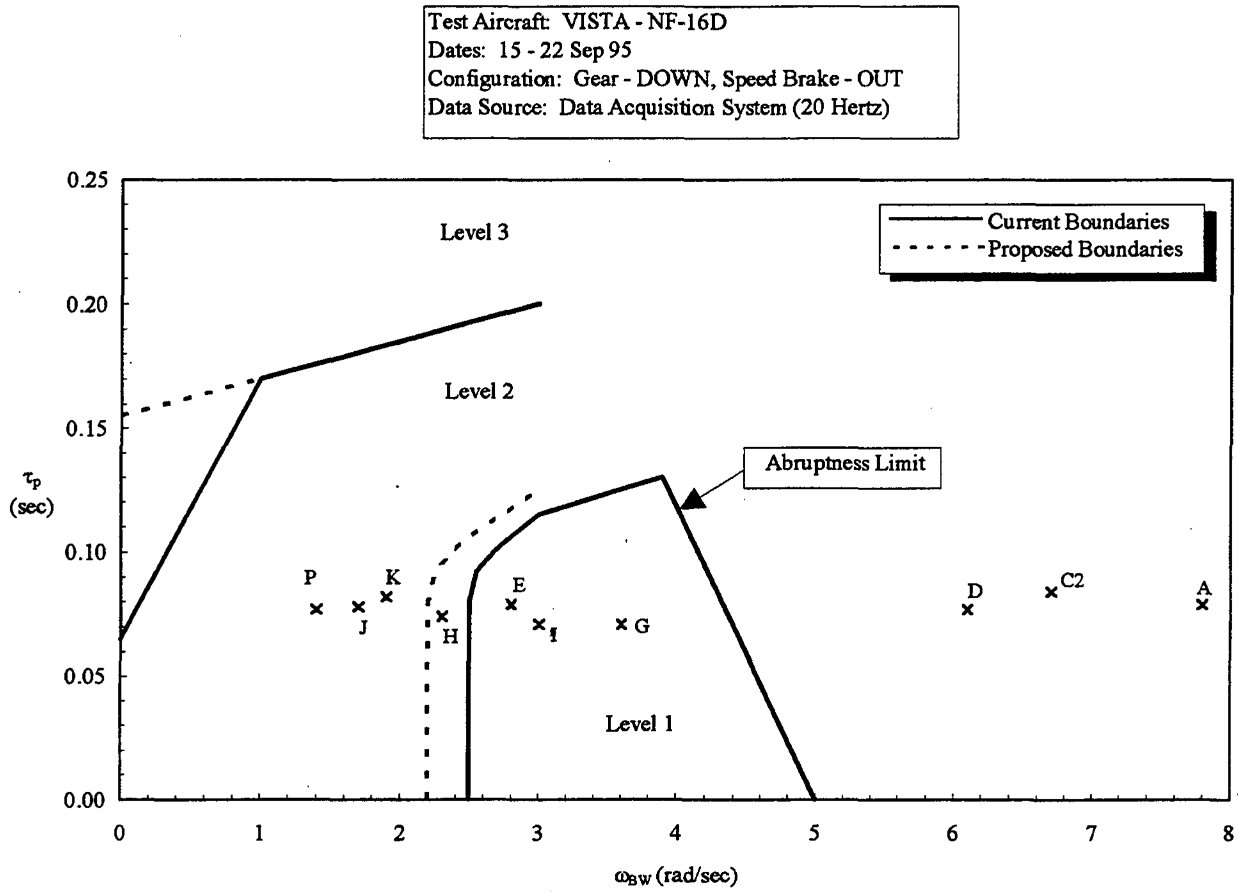


Figure 29 Location of VSS Configurations on the Bandwidth Space

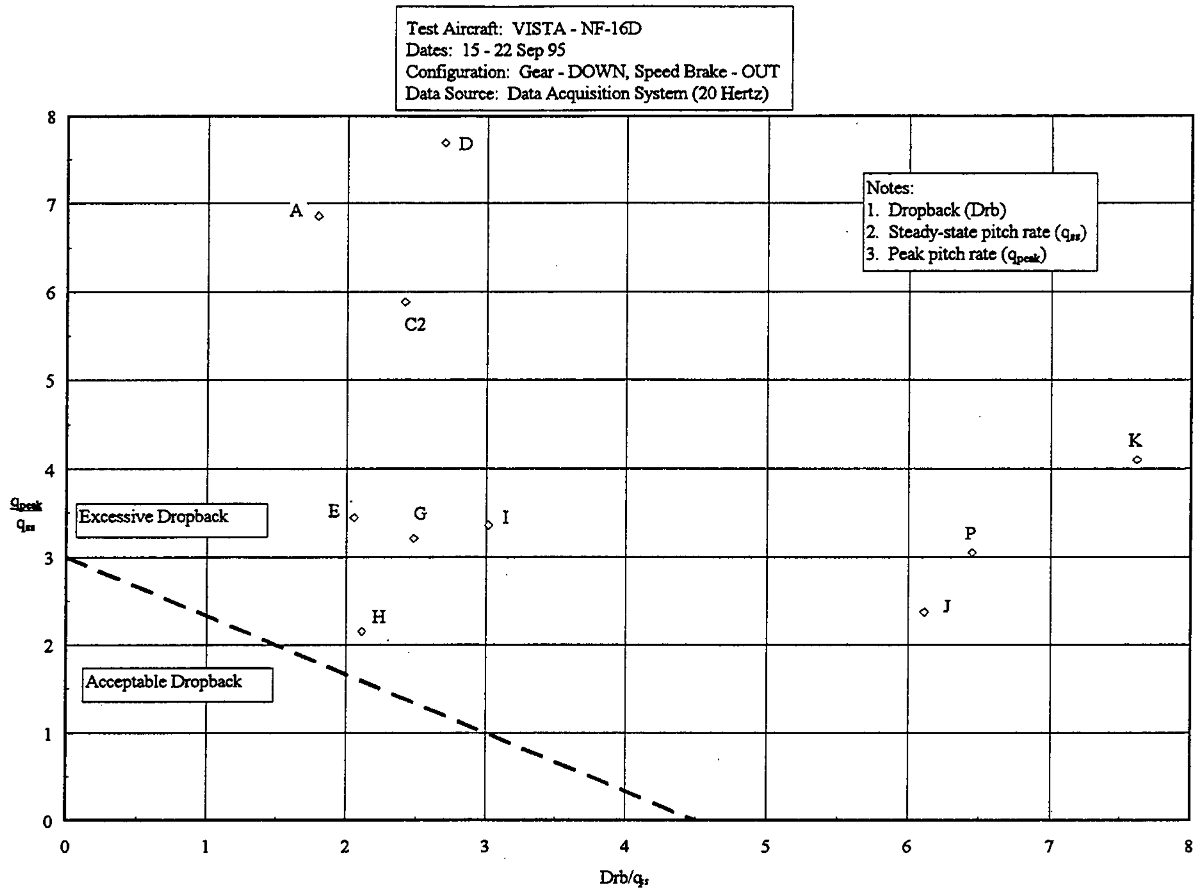


Figure 30 Location of VSS Configurations on the Dropback Space

6.2 VSS Configuration Evaluations

Qualitative and quantitative pilot comments were obtained for the ten VSS configurations during the offset landing task. The quantitative data consisted of Cooper-Harper and PIO ratings. Cooper-Harper and PIO ratings are presented for all configurations in Figure 31 and Figure 32. AFFTC-TR-95-78 contains a database of all pilot comments and the details of each landing evaluation flown [27].

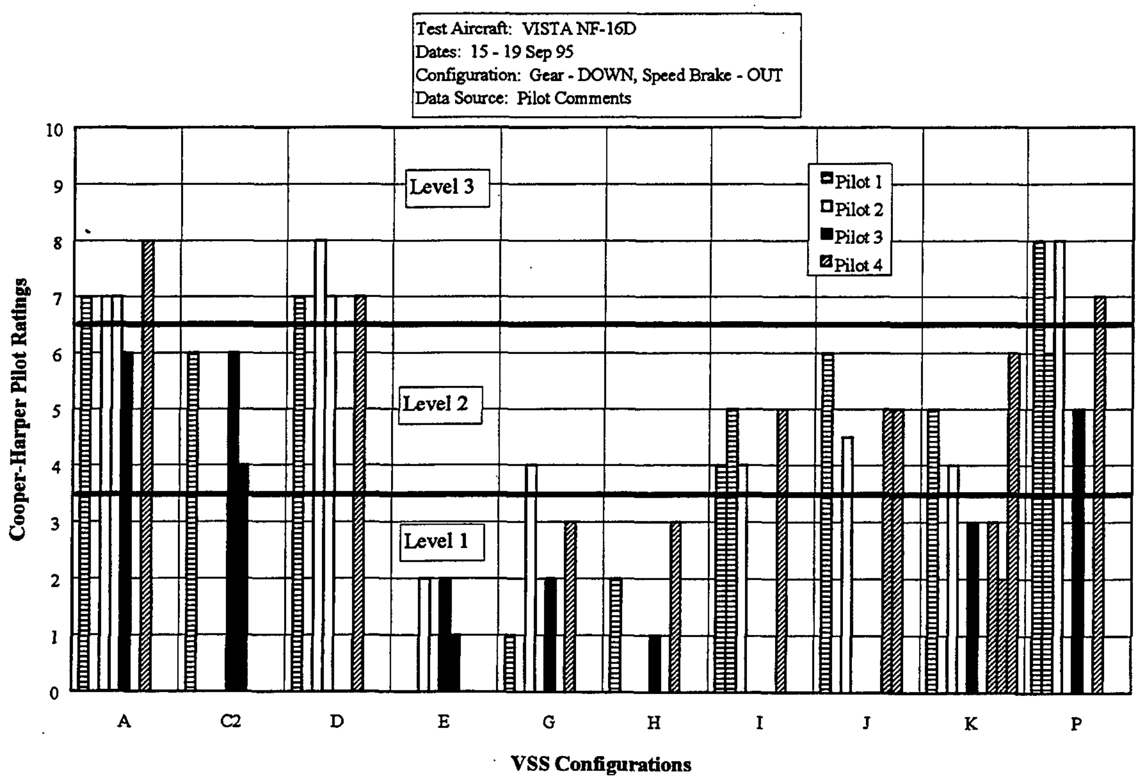


Figure 31 Cooper-Harper Ratings

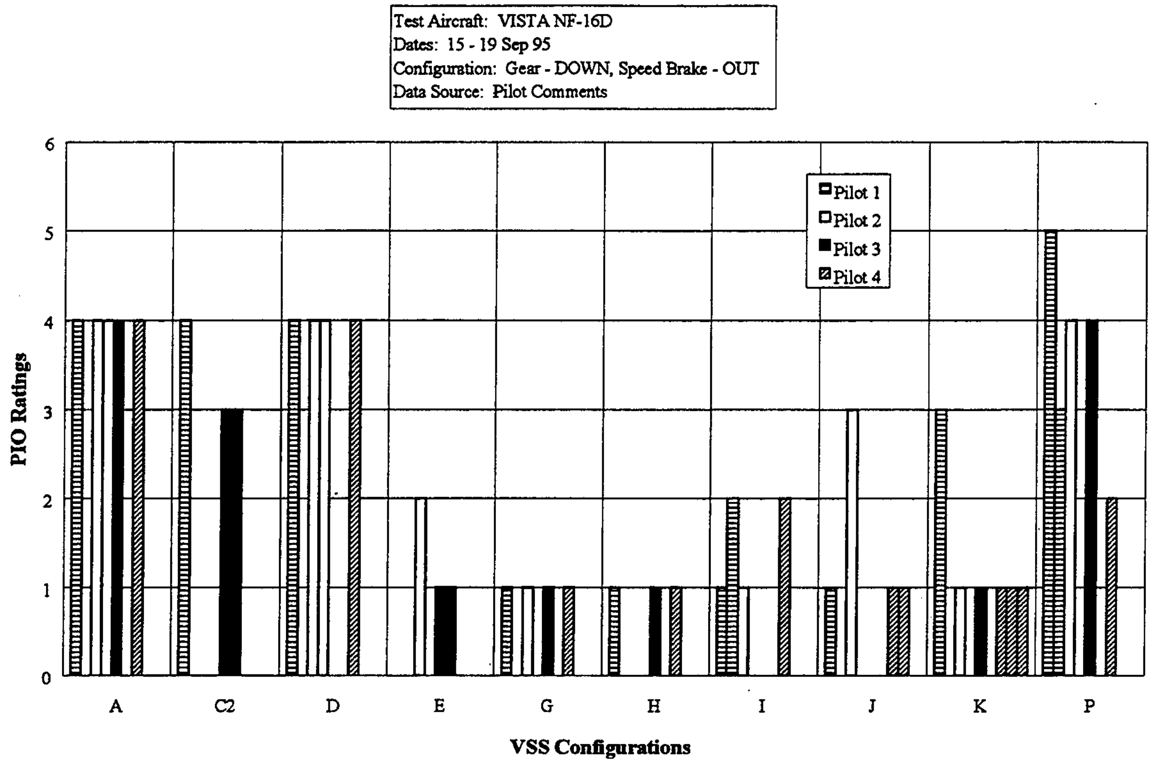


Figure 32 Pilot Induced Oscillations Ratings

The following text presents a synopsis of pilot comments by aircraft configuration. For each configuration, Table 11 through Table 20 present a summary of pilot ratings, as well as the predicted handling qualities level (1, 2 or 3) according to each of the CAP, bandwidth and bandwidth with dropback criteria. In addition, the tables list the short period natural frequency (ω_{sp}) and damping ratio (ζ_{sp}), bandwidth frequency (ω_{BW}) and phase delay (τ_p) for each VSS configuration. Where a single pilot evaluated a given configuration on more than one occasion, pilot ratings given on each evaluation are listed in order separated by commas.

Pilot comments are summarized for each configuration in three paragraphs. The first describes the dominant comments common to all or most of the pilots for that VSS configuration, followed by the effect on pilot technique and task performance. Subsidiary pilot comments, such as those noted by only one or two pilots for that configuration are then discussed. Where warranted, further engineering analysis is given in a fourth paragraph.

6.2.1 VSS Configuration A

Table 11 VSS Configuration A—Summary of Results

<table>
<tr><td colspan="4">Predicted Level: CAP: 2 Bandwidth: 2 Proposed Bandwidth w/ Drb[1]: 2</td></tr>
<tr><td colspan="4">Dynamics: ω_{sp}: 5.68 ζ_{sp}: 0.384 ω_{BW}: 7.8 τ_p: 0.079 τ_θ: 0.040</td></tr>
<tr><td>Pilot</td><td>Cooper-Harper Rating</td><td>Handling Qualities Level</td><td>PIO Rating</td></tr>
<tr><td>1</td><td>7</td><td>3</td><td>4</td></tr>
<tr><td>2</td><td>7, 7</td><td>3, 3</td><td>4, 4</td></tr>
<tr><td>3</td><td>6</td><td>2</td><td>4</td></tr>
<tr><td>4</td><td>8</td><td>3</td><td>4</td></tr>
</table>

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: All pilots found this configuration sensitive or touchy, with a small amplitude, quick pitch bobble or PIO being generated soon as they entered the loop even with small inputs. This pitch bobble could not be avoided in closed loop flight—Pilot 1 noted that even trim actuation excited the pitch bobble. Most pilots reported that aggressiveness aggravated the bobble. Pilot 2 on two separate evaluations reported that aggressiveness only slightly worsened the problem or did not effect it beyond a certain limiting amplitude. Pilot 4 reported a PIO on one evaluation.

Pilot performance: The net result of this characteristic was that pilot workload was intolerably high, with considerable compensation variously reported as "lag" or "lag-lead compensation," "tight in the loop control with small inputs," and "smoothing and lowering" of pilot gains. Pilot 2 reported a strong tendency to back out of the loop to avoid aggravating the bobble, resulting in less precise aircraft control and degraded task performance. Desired criteria were met on only six out of 14 landings.

Subsidiary pilot comments: Pilot 2 (on two evaluations of this configuration) and Pilot 3 reported that despite the pitch sensitivity the flight path did not respond rapidly enough. This disparity between the initial and final steady-state response was taken by the flight test team as an indication of excessive dropback. Predictability was reported as poor by these two pilots. Due to encountering a divergent PIO, Pilot 4 considered control was in question and assigned the Cooper-Harper rating of 8.

Additional analysis: The time histories of Pilot 4's PIO are presented Appendix D. The pilot first entered a PIO during the offset maneuver. However, there was sufficient altitude for the pilot to back out of the loop and recover from the PIO. A second PIO was encountered in the flare. This time the pilot did not back out of the loop due to the close proximity of the ground.

6.2.2 VSS Configuration C2

Table 12 VSS Configuration C2—Summary of Results

Predicted Level: CAP: 2	Bandwidth: 2	Proposed Bandwidth w/ Drb[1]: 2	
Dynamics: ω_{sp}: 4.97 ζ_{sp}: 0.632	ω_{BW}: 6.7	τ_p: 0.084	τ_θ: 0.075
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	6	2	4
2	-	-	-
3	6, 4	2, 2	3, 3
4	-	-	-

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Both evaluation pilots found this configuration sensitive, and reported a pitch bobble that was not divergent. Pertinent comments were "jittery and bouncy" (Pilot 1), and "nervous—darting up and down—extremely sensitive" (Pilot 3). In addition, both reported a tendency to overshoot and an inability to place the nose where required as the aircraft "gives you more than you wanted" in pitch (Pilot 3). These comments are again indicative of excessive dropback. The pitch bobble was non-divergent and could be damped with the pilot in the loop. Aggressiveness excited the motion.

Pilot performance: The result of this was a requirement for small inputs or backing out of the loop combined with anticipation. However, task performance did not appear to be greatly impacted: seven desired criteria touchdowns were achieved in nine landings. Nevertheless, at least one landing which did not meet either desired or adequate criteria was directly attributed by Pilot 3 to being forced out of the loop by the "squirrely" aircraft each time he tried to "get in the loop."

Subsidiary pilot comments: Control harmony was also reported as poor by both pilots indicating a discrepancy between control forces and handling qualities in the lateral and longitudinal axes. Though the lateral axis of the VISTA was not under study, poor control harmony may have adversely effected pilot opinion of the configuration overall.

6.2.3 VSS Configuration D

Table 13 VSS Configuration D—Summary of Results

Predicted Level: CAP: 2	Bandwidth: 2	Proposed Bandwidth w/ Drb[1]: 2	
Dynamics: ω_{sp}: 5.40, ζ_{sp}: 0.290	ω_{BW}: 6.1	τ_p: 0.077	τ_θ: 0.080
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	7	3	4
2	8, 7	3, 3	4, 4
3	-	-	-
4	7	3	4

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: This VSS configuration was sensitive in the pitch axis with a high frequency pitch oscillation or bobble noted by all pilots and described as small or low amplitude. It was excited "with every little input—actuating the trim button causes undesirable motions" (Pilot 1) and was "very difficult to prevent" (Pilot 2). All pilots reported that aggressiveness or tighter control worsened the bobble. Pilot 2 on his second evaluation reported that once excited to a given amplitude, further aggressiveness did not exacerbate the bobble.

Pilot performance: This resulted in smoothing of inputs or more open loop control. Pilot 1 reported devoting much attention to control of the pitch axis. All pilots

reported backing out of the loop in the flare to avoid these unpleasant motions. Seven out of 12 approaches met desired criteria but workload was considered intolerably high by all pilots.

Subsidiary pilot comments: Pilots 1 and 2 reported problems with sustained maneuvering ability despite the initial pitch sensitivity indicating excessive dropback. Pilot 1 noted the stick forces were high despite the sensitivity, particularly in the offset maneuver and flare. Pilot 2 noted during both his evaluations of this configuration a sluggishness in sustained maneuver, and also attributed some deterioration in task performance to this feature. Pilot 1 considered the motions controllable and predictable, while Pilot 2 considered the aircraft response overall unpredictable because of the difference between initial sensitivity and sluggish sustained maneuver. Pilot 2 also reported increasing the size of pitch inputs to compensate for the sluggishness after initial smoothing to avoid exciting the bobble.

6.2.4 VSS Configuration E

Table 14 VSS Configuration E—Summary of Results

Predicted Level:	CAP: 1	Bandwidth: 1	Proposed Bandwidth w/ Drb[1]: 2
Dynamics:	ω_{sp}: 2.18 ζ_{sp}: 0.523	ω_{BW}: 2.8 τ_p: 0.079	τ_θ: 0.072
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	-	-	-
2	2	1	2
3	2, 1	1, 1	1, 1
4	-	-	-

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Both pilots reported good handling qualities with negligible deficiencies or better.

Pilot performance: Pilot 3 even adjusted the task in an attempt to increase pilot gains, but still effectively met desired criteria on all six approaches. Pilot 2 met adequate criteria on two of three approaches without reporting a reason, however this was his first evaluation of the program and he was consequently less familiar with the task.

Subsidiary comments: The only deficiencies noted were a very slight pitch bobble on two of the three approaches flown by Pilot 2, and not as crisp as ideal pitch control noted by Pilot 3 on his first evaluation. While this may be an indication of excessive dropback, it did not significantly degrade either pilots' rating since each pilot rated the VSS configuration as a Level 1 configuration. This is supported by Figure 30 which shows configuration E lay closer to the region of acceptable dropback than configurations A, C2, and D. In these three configurations (A, C2, and D), pilot comments were

indicative of excessive dropback and pilot ratings were in the handling qualities Level 2 and 3 regions.

6.2.5 VSS Configuration G

Table 15 VSS Configuration G—Summary of Results

Predicted Level: CAP: 1	Bandwidth: 1	Proposed Bandwidth w/ Drb[1]: 2	
Dynamics: ω_{sp}: 2.50	ζ_{sp}: 0.785 ω_{BW}: 3.6	τ_p: 0.071	τ_θ: 0.078
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	1	1	1
2	4	2	1
3	2	1	1
4	3	1	1

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Pilots found this to be a "good flying" configuration as reflected in the Cooper-Harper ratings. However, three of four pilots reported the configuration to be slightly sluggish, with control forces heavier than desired. Pilot 4 noted that quicker response might have made the task easier, with similar comments from Pilot 3. Pilot 2 described a mushiness or lagginess in response. No further deficiencies were noted. Pilot 1 found no deficiencies at all.

Pilot performance: Six out of 12 approaches met desired criteria, indicating the pilots may have had more trouble with this configuration than they themselves identified. However, no firm conclusions can be drawn since any number of reasons might account for these results. Though Pilot 1 failed to achieve even adequate criteria on one approach, this was on his first approach in the program when he was less familiar with the task. Pilot

4, again on his first evaluation of the program, attributed two adequate approaches to premature power reduction, though his angle of attack (AOA) on one of these was low (i.e. fast), perhaps indicating the configuration was in fact giving insufficient pitch response, or simply that he was still relatively unfamiliar with the task. Finally, some doubt must be expressed as to the validity of Pilot 3's Cooper-Harper rating of 2. This rating was assigned after the pilot noted some sluggishness, commented on increased workload and achieved only one desired criteria approach out of three.

Subsidiary comments: Pilot 2 noted that despite the sluggishness, initial pitch response was good indicating some discrepancy between initial and sustained response.

Additional analysis: The comments point to a low steady state pitch rate compared to the initial pitch rate—or a tendency towards excessive dropback. As in VSS configuration E, configuration G's dropback lay closer to the acceptable region as shown in Figure 30 and seems to have had less impact on pilot opinion than the greater dropback configurations A, C2, and D. Given the task criteria achieved, dropback may have affected task performance more than the evaluation pilots realized.

6.2.6 VSS Configuration H

Table 16 VSS Configuration H—Summary of Results

Predicted Level: CAP: 1 Bandwidth: 2 Proposed Bandwidth w/ Drb[1]: 2			
Dynamics: ω_{sp}: 2.29 ζ_{sp}: 0.967 ω_{BW}: 2.3 τ_p: 0.074 τ_θ: 0.070			
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	2	1	1
2	-	-	-
3	1	1	1
4	3	1	1

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: This VSS configuration was noted as a Level 1 configuration with few deficiencies and overall good pilot comments.

Pilot performance: Seven out of nine approaches met desired landing criteria. One instance of adequate criteria being met was on Pilot 3's first evaluation of the program, when he was less familiar with the task. Overall, consistently good results were achieved in the landing task.

Subsidiary comments: Pilot comments on deficiencies were mixed—Pilot 1 felt the pitch response to be a little slow but with "good command authority," while Pilot 4 felt it was too quick initially with a slightly slow steady-state response. Despite the apparent discrepancy here, the comments may in fact represent the same phenomenon: good initial pitch motion (or command authority) with slightly low sustained response. This again indicates excessive dropback, but as in configurations E and G the level of dropback encountered did not cause pilot opinion to drop below overall Level 1 ratings. It did, however, cause Pilots 1 and 4 to assign less than perfect Cooper-Harper ratings attributed

directly to a "minor deficiency with pitch command rate" (Pilot 1) or because "the pitch response was mildly unpleasant" (Pilot 4). Pilot 3 felt there were no deficiencies. As seen in Figure 30, configuration H lay closest to the acceptable dropback region and is supported by the comments above.

6.2.7 VSS Configuration I

Table 17 VSS Configuration I—Summary of Results

Predicted Level: CAP: 1 Bandwidth: 1 Proposed Bandwidth w/ Drb[1]: 2			
Dynamics: ω_{sp}: 3.28 ζ_{sp}: 0.830 ω_{BW}: 3.0 τ_p: 0.071 τ_θ: 0.085			
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	4, 5	2, 2	1, 2
2	4	2	1
3	-	-	-
4	5	2	2

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Principal comments on this configuration indicated the VSS configuration was sluggish, but with a disparity between initial pitch response (Pilot 1: "too quick," Pilot 2: "about right") and slower maneuver response (Pilot 1: "good AOA command," Pilot 2: "slow response for maneuver"). While this was identified by Pilots 1 and 2, Pilot 4's comments strongly stressed the sluggishness of maneuver response: "couldn't get the motion desired so had to pull more." Note, though Pilot 1 considered the maneuver response sufficient, stick forces were considered too high. Given the stick force gradient was the same for all VSS configurations tested, this may indicate that Pilot 1 also found the maneuver response too slow but did not identify it as such.

Pilot performance: Eight out of 12 landings met desired criteria, showing degraded performance over other VSS configurations which were rated as Level 1, possibly as a result of the sluggish maneuver response. Pilot 4 particularly noted that in the flare he was "trying to let the aircraft down but couldn't get the nose down with smooth small motions."

Subsidiary comments: In addition to the above comments, Pilots 1 and 4 noticed a pitch bobble. Pilot 4 found this only on the third landing and considered it easily compensated for, while Pilot 1 stated it was very distracting but did not compromise task performance. Pilot 2 did not identify this problem. It should be noted that Pilot 1's first evaluation of the configuration (also the first test point of the program) did not identify any of these deficiencies, but noted a tendency towards high angles of attack in the flare. This may have indicated a higher workload than Pilot 1 realized leading to poorer power and energy control.

Additional analysis: Once again pilot comments support the inference that this configuration had excessive dropback. This conclusion can be drawn from all pilots' comments more clearly than for some other VSS configurations where only one or two pilots noted characteristics associated with high dropback. This may indicate that pilots are sensitive to increasingly excessive dropback in this region.

6.2.8 *VSS Configuration J*

Table 18 VSS Configuration J—Summary of Results

Predicted Level: CAP: 3	Bandwidth: 2	Proposed Bandwidth w/ Drb[1]: 3	
Dynamics: ω_{sp}: 1.44 ζ_{sp}: 0.214	ω_{BW}: 1.7	τ_p: 0.078	τ_θ: 0.066
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	6	2	1
2	4.5	2	3
3	-	-	-
4	5, 5	2, 2	1, 1

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Pilot comments were unanimous in identifying this VSS configuration as slow or sluggish. Pilot 1 reported he "ran out of pitch power in flare," while Pilot 4 stated he "could not get the nose authority I wanted."

Pilot performance: This slow response gave just four desired criteria landings out of 12 approaches with both touchdown firmness and landing zone position responsible for this performance in roughly equal proportions. Pilot 4 reported touching down firm and fast due to the slow response using a variety of pilot techniques (high gain and low gain).

Subsidiary comments: Pilot 2 reported the slow aircraft response resulted in over control and slow oscillations about target pitch attitudes and during the offset correction to centerline, AOA excursions. These characteristics can be explained in terms of the slow pitch response—an input was made, the aircraft did not seem to respond and the size of the input was increased just as the pitch axis began to move, resulting in over control in pitch or AOA. Table 18 shows Pilot 2 gave this VSS configuration a Cooper-Harper rating of 4.5. Justification for this rating was the configuration required more than

moderate compensation for desired performance, however considerable compensation was not required to achieve adequate performance. Thus, the pilot felt a rating of 4.5 was the most accurate rating for this VSS configuration. Refer to Appendix A for the Cooper-Harper Pilot Rating Scale.

Additional analysis: As seen in Figure 30, this configuration was predicted to have excessive dropback. However, due to the slow time response the evaluation pilots were not able to break out the difference between the initial and steady-state response. Thus, dropback did not appear to be a factor in pilot rating for this configuration as supported by the above comments.

6.2.9 VSS Configuration K

Table 19 VSS Configuration K—Summary of Results

Predicted Level: CAP: 1	Bandwidth: 2	Proposed Bandwidth w/ Drb[1]: 3	
Dynamics: ω_{sp}: 1.44 ζ_{sp}: 0.555	ω_{BW}: 1.9	τ_p: 0.082	τ_θ: 0.066
Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
1	5	2	3
2	4	2	1
3	3	1	1
4	3, 2, 6	1, 1, 2	1, 1, 1

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: Overall this was assessed as slow or sluggish. Pilot 2 simply assessed the aircraft as sluggish with no further deficiencies. Pilots 1 and 4 noted some form of apparent delay (Pilot 1: "a small lag," Pilot 4: "response seemed to ramp up"). Pilot 3 commented in a different way on the same phenomenon stating that "small stick

movements produced no movement of the nose." This comment may reflect the slow response of the configuration to initial inputs requiring an increase in stick movement from the pilot, which then appeared to generate the aircraft movement that was in fact the slow response from the initial input. However, from the LOES match, the configuration had an equivalent delay of 0.066 second, which was within MIL-STD-1797A recommendations for acceptable delay. Thus, the configuration's time delay did not necessarily explain pilot comments of sluggishness.

Pilot performance: Both Pilots 3 and 4 reported using a technique comparable with lead compensation—an oversized initial input followed by a check in the opposite direction. Pilot 1 also described using lead compensation. Ten out of 19 approaches met desired criteria. Workload and pilot compensation required were the main factors in the assigned pilot ratings.

Subsidiary comments: Pilots 1 and 3 commented on some form of undesirable pitch motions. Pilot 1 directly assessed this as a tendency to overshoot desired pitch attitudes due to the larger inputs required to counter the slow aircraft response. It should also be noted that Pilot 4 assessed this configuration on three separate occasions and pilot ratings were somewhat inconsistent. On the first evaluation of this configuration the pilot felt there was a deficiency but was not able to identify it. Only the second look at the configuration (Cooper-Harper 2 assigned) was inconsistent with other pilot comments; on this the pilot reports using a low gain technique.

Additional analysis: The safety pilot noted on Pilot 4's last evaluation of this configuration (Cooper-Harper 6 assigned) the pilot seemed more fatigued than usual.

Thus, the pilot was either more aware of the compensation technique or was unable to compensate as well when fatigued. The safety pilot noted that Pilot 4 adopted a low gain technique—placing the aircraft close to desired parameters and then backing out of the loop and accepting what the aircraft gave him. Even though Pilot 4's Cooper-Harper ratings showed a wide range, it seems the pilot found a deficiency on one evaluation which he was better able to compensate for without noticing when less fatigued.

6.2.10 VSS Configuration P

Table 20 VSS Configuration P—Summary of Results

Pilot	Cooper-Harper Rating	Handling Qualities Level	PIO Rating
Predicted Level: CAP: 1	Bandwidth: 2	Proposed Bandwidth w/ Drb[1]: 3	
Dynamics: ω_{sp}: 1.20 ζ_{sp}: 0.435	ω_{BW}: 1.4	τ_p: 0.077	τ_θ: 0.066
1	8, 6	3, 2	5, 3
2	8	3	4
3	5	2	4
4	7	3	2

Note: 1. Proposed Bandwidth w/ Drb means Proposed Bandwidth with Dropback

Main comments: All pilots noted either a PIO (Pilots 1, 2 and 3) or pitch bobble (Pilot 4). This was stressed as a very strong tendency by Pilots 1, 2 and 3. Pilot 2 described the pitch axis as very sensitive—but at a low frequency of response. Pilots 1 and 3 also described the response as slow, with Pilot 1 reporting running out of "pitch command" in the flare. Aggressiveness was reported to exacerbate the PIO by all pilots.

Pilot performance: The result of this was that workload was high, significant compensation being required in the form of smoothing (Pilots 1, 2 and 3) and "backing out

of the loop" (Pilots 1 and 2). Pilot 4 reported using small quick inputs. Only six out of 16 landings met desired criteria due to both touchdown firmness and position.

Subsidiary comments: Pilot 2 felt control was in question. Pilot 1 also felt control was in question on his first evaluation of the configuration, but not on his second. However, on this second evaluation a PIO of sufficient amplitude to trip the VSS was encountered.

Up to this point, characteristics of each individual VSS configuration have been analyzed. The following sections take common characteristics found among groups of configurations and draws trends and conclusions among them.

6.3 Trends from Flight Test Results

6.3.1 High Frequency Trends (VSS Configurations A, C2, and D)

Pilot comments for the high frequency VSS configurations (A, C2, and D) included an initial quick response followed by a slow or sluggish steady-state response. The pitch attitude of the aircraft was sensitive while the flight path was sluggish. Both of these comments characterized the VSS configurations as having excessive dropback. Applying the dropback definition to the VSS configurations predicted them to have excessive dropback.

Configuration C2 had more favorable pilot ratings than A and D, and was not considered as pitch sensitive. Pilots reported that the pitch oscillation in C2 could be damped by pilot inputs, while for configurations A and D the oscillations were very

difficult to avoid. In the CAP domain this correlates to a low damping. In the bandwidth domain, both points satisfied the two criteria needed for the discontinuous jump—both were gain limited and had a non-monotonic gain pitch attitude to pitch manipulator Bode plots. Thus, their handling qualities were predicted to be poor due to the shape of the Bode magnitude plots (16:231). In the dropback domain, the worse pilot ratings may be attributed to excessive dropback.

Using the mode of pilot ratings, or the pilot rating with the greatest frequency, the actual handling qualities levels are shown in Table 21. Note that all evaluation pilots agreed upon the aircraft handling qualities levels except for VSS configuration A. Four evaluations gave this configuration a Level 3 rating while one gave the configuration a Level 2 rating. Table 21 also presents the CAP, bandwidth and bandwidth with dropback criteria predictions.

Table 21 High Frequency VSS Configurations' Handling Qualities Levels

VSS Configuration	Mode of Actual Pilot Opinion	Predictive Metric		
		CAP	Bandwidth	Proposed Bandwidth with Dropback
A	3	2	2	2
C2	2	2	2	2
D	3	2	2	2

Table 21 shows CAP and bandwidth both matched the actual VSS configuration C2 handling qualities level. Applying the dropback definition to configuration C2 preserved the predictive Level 2 rating. Applying the dropback definition to VSS configurations A and D increased the predictive ratings to Level 2 which agreed with both the CAP and bandwidth metrics. However, the evaluation pilots felt those two configurations had Level 3 handling qualities. Thus, all methods under-predicted the actual handling qualities of configurations A and D.

In summary, the bandwidth criterion with and without applying the dropback criterion correctly matched pilot opinion of VSS configuration C2, or the high frequency point without a non-monotonic Bode magnitude plot. The evaluation pilots gave Level 3 ratings to both VSS configurations A and D, which satisfied both jump conditions—being gain limited and having a non-monotonic Bode magnitude plot. Bandwidth with dropback incorrectly matched VSS configurations A and D. Thus, these flight test results indicate a non-monotonic type Bode plot, as in VSS configuration A and D, indicate Level 3 handling qualities rather than the magnitude of bandwidth.

VSS configurations A and D also had PIO tendencies. Both configurations had PIO ratings of 4, indicating the oscillations were not divergent. All evaluation pilots commented that these configurations had the tendency to pitch bobble or PIO as pilot aggressiveness increased.

During one landing of VSS configuration A, the variable stability system disengaged due to a growing oscillation. The first encounter occurred just as the pilot aggressively corrected back to centerline during the lateral offset. A divergent PIO was

not encountered during this maneuver since the pilot had enough altitude to back out of the loop and re-enter the loop slowly, as shown in the stick deflection plot in Appendix D, Figure 46. The second instance where a PIO was encountered with VSS configuration A was during the flare, again shown in Figure 46. This time the pilot did not back out of the loop due to the close proximity of the ground. A divergent PIO was encountered and resulted in the approach being terminated when the VSS transferred control to the safety pilot. The PIO rating of 4 on this approach was a result of the extremely short time period of the PIO and the inability of the evaluation pilot to determine if the oscillations were divergent. It was not until post flight analysis that it was realized the oscillations were divergent.

Time traces of the left and right horizontal stabilators, refer to Figure 47, show the classical sawtooth form of a rate limit. Plotting the derivative of each stabilators' deflection versus time shows those areas where the stabilators were rate limited. As the surface reached the rate limit its derivative reached and remained at the maximum rate—approximately 70 deg/sec for VISTA. This is shown as a constant horizontal line on the derivative time traces. As shown in Figure 48, the first PIO did not result in rate limiting. Figure 49 shows the second PIO had 0.7 second of rate limiting before the VSS transferred control to the safety pilot. However, the important point was the divergent nature of the PIO began before the stabilators were rate limited.

6.3.2 Mid Frequency Trends (VSS Configurations E, G, H, and I)

The VSS configurations E, G, H and I lay within the "heart" of both the CAP and bandwidth domains. All configurations were predicted to have excessive dropback. Pilot comments indicated that VSS configuration I clearly had excessive dropback while configurations G and H were in an area where excessive dropback was noticed by some but not all pilots. One evaluation pilot out of four for configuration G and one out of three for configuration H commented that initial nose movement was good while it was slow or sluggish in the steady-state response, thus indicating excessive dropback. As shown in Figure 30, configurations G and H lay closer to the proposed dropback line. Configuration E had no pilot comments which indicated excessive dropback despite the prediction of excessive dropback.

The mode of actual pilot opinion revealed trends among the predictive handling qualities criteria for these four configurations. The mode along with the predictive handling qualities are presented in Table 22. Generally, the evaluation pilots rated VSS configurations E, G, and H the best out of all evaluated VSS configurations stating the aircraft had good predictable initial and steady-state responses.

All evaluation pilots gave these four VSS configurations the same handling qualities rating except for Pilot 2 who gave configuration G a Level 2 rating while the three other pilots rated the configuration as Level 1. Justification for the Level 2 rating was due to the "slight mushiness/lagginess" in the steady-state response. This caused the pilot to over control initial inputs and approach the AOA test limit of 13°. To prevent

these undesirable AOA excursions, the pilot was required to compensate by anticipating aircraft response.

Table 22 Mid Frequency VSS Configurations' Handling Qualities Levels

VSS Configuration	Mode of Actual Pilot Opinion	Predictive Metric		
		CAP	Bandwidth	Proposed Bandwidth with Dropback
E	1	1	1	2
G	1	1	1	2
H	1	1	2	2
I	2	1	1	2

As seen in Table 22, both the CAP and bandwidth criteria matched actual pilot opinion for VSS configurations E and G. The evaluation pilots noticed excessive dropback on all configurations except VSS configuration E. However, though the evaluation pilots noticed characteristics of excessive dropback their performance did not appear to be compromised. They felt these VSS configurations had good, well-defined, and predictable handling qualities. These comments also support Figure 18 and Figure 19 which show that application of the dropback criterion for CAP Level 1 aircraft decreased the theoretical area of agreement between the criteria. Applying the dropback definition to bandwidth resulted in a conservative prediction for configurations E, G, and H because

of their excessive dropback. Thus, results indicate application of the dropback criterion to VSS configurations E, G and H did not help predict pilot opinion.

Increasing ω_{sp} and ω_{BW} from configuration H to I, as shown in Figure 28 and Figure 29, resulted in worse handling qualities. Because of the worse handling qualities and noticeable dropback, the dropback criterion should be applied to VSS configuration I. These results may indicate the dropback criterion should be applied to those aircraft which lay above VSS configuration H in the CAP domain. Results from this flight test are not sufficient enough to determine the exact location where dropback should be applied. However, results do indicate pilot opinion began to be influenced by excessive dropback between an ω_{sp} of 2.3 and 3.3 rad/sec and between a CAP value of 1.31 and 2.68/g*sec^2.

6.3.3 Low Frequency Trends (VSS Configurations J, K, and P)

The VSS configurations J, K, and P lay in the lower frequency range of CAP as shown in Figure 28. These points also had low bandwidths, lying to the left of the bandwidth Level 1 region shown in Figure 29.

Configuration K lay between a Level 1 and 2 aircraft; three evaluations pilots rated the configuration Level 1, while three rated the configuration Level 2. All evaluation pilots gave the configuration a PIO rating of 1 except Pilot 1 who gave the configuration a PIO rating of 3, meaning undesirable motions compromised task performance. The PIO rating of 3 was assigned because of undesirable pitch motions. These motions were due to the required large, fast control inputs compensating for the slow pitch response.

Pilot 4 flew the configuration three times assigning Cooper-Harper ratings of 3, 2 and 6. He flew this configuration during the sixth evaluation on his first sortie and during the second and fifth evaluations one his second sortie. During the first evaluation Pilot 4 commented, "There was something I didn't like, but couldn't put my finger on it." During the second evaluation he commented the configuration had a good, predictable initial response. During the third evaluation he commented the configuration was slow initially and then would ramp up to a quick steady-state. This unpredictably required extensive pilot compensation that mandated improvement. The safety pilot noted Pilot 4 seemed more fatigued during the third evaluation and that he changed his compensation techniques between the second and third evaluations. The safety pilot stated that during the first landing of the third evaluation Pilot 4 was in a PIO reaching 14° AOA. After this landing, Pilot 4 changed his technique and quit flaring the aircraft and began to accept harder landings. Thus, it seemed that Pilot 4 found what it was that he did not like during the first evaluation when he was more fatigued.

Decreasing the damping ratio from VSS configuration K to J resulted in a solid Level 2 rating by the evaluation pilots. Pilot comments indicated the decrease in pilot opinion resulted from the slow response and resulting over control and pitch overshoots. This over control led to AOA excursions during the initial offset correction. As a result the evaluation pilots had harder touchdowns because of a lack of pitch response in the flare. As shown in Table 23, the bandwidth criterion matched pilot opinion for VSS configurations K and J. Pilot comments did not indicate excessive dropback. Because of the configurations' slow time response, the evaluation pilots did not notice excessive

dropback even though application of the dropback definition predicted excessive dropback.

Table 23 Low Frequency VSS Configurations' Handling Qualities Levels

CAP	Mode of Actual Pilot Opinion	Predictive Metric		
		CAP	Bandwidth	Proposed Bandwidth with Dropback
K	1, 2	1	2	3
J	2	3	2	3
P	3	1	2	3

Decreasing the short period frequency from VSS configuration K to P resulted in a decrease in the mode of pilot opinion rating to Level 3. Two evaluation pilots rated configuration P as a Level 2 aircraft even though pilot compensation was high and the aircraft had the tendency to PIO. The PIO ratings ranged from 2 to 5. Pilot comments did not indicate excessive dropback. Once again, the configuration's time response was too slow for pilots to judge the total response. Pilot comments centered around the configuration's very slow response and tendency to overshoot, resulting in PIO's. Pilot aggressiveness was a factor in the amplitude of PIO's. Compensation techniques were to back out of the loop allowing the aircraft to fly itself down the glideslope as much as possible. Applying the dropback definition to configuration P resulted in a correct match.

However, this match was due to the wrong reasons. The evaluation pilots did not notice excessive dropback for this configuration, thus the definition should not be applied.

In summary, VSS configuration K was a borderline Level 1, Level 2 configuration. Decreasing the damping from K to J resulted in a clearly Level 2 aircraft. Although configuration J had excessive dropback, it was not noticed due to the slow response of the configuration. Decreasing the short period frequency from K to P resulted in three ratings as a Level 3 aircraft and two ratings as a Level 2 aircraft. However, all evaluation pilots commented on the susceptibility of a PIO during the maneuver.

6.4 CAP and Bandwidth Prediction Correlation Results

Overall, the CAP and bandwidth criteria had a 50% prediction correlation on the actual pilot's statistical mode while bandwidth with dropback had a 30% prediction correlation as shown in Table 24. When CAP and bandwidth with dropback agreed or bandwidth and bandwidth with dropback agreed, there was a 25% prediction correlation on the pilot's statistical mode. When CAP agreed with bandwidth there was a 50% prediction correlation.

For the high frequency configurations (A, C2 and D), all predictive methods agreed however only configuration C2's prediction matched pilot opinion. The CAP and bandwidth predictions agreed for the mid-frequency configurations (E, G, and I). Actual pilot comments indicated only configurations E and G matched predictions. The CAP and bandwidth predictions for configuration I agreed but bandwidth with dropback matched pilot opinion. Bandwidth and bandwidth with dropback predictions agreed for

configuration H but CAP matched pilot opinion. For the low frequency VSS configuration J, CAP and bandwidth with dropback predictions agreed, however, bandwidth matched pilot opinion. Bandwidth with dropback incorrectly predicted pilot opinion because it predicted excessive dropback when pilot comments did not support excessive dropback.

Table 24 presents one additional predictive metric—"Bandwidth with Modified Dropback." It was noticed after analyzing flight test results that pilot ratings were degraded due to excessive dropback only for those configurations which lay above VSS configuration I in the CAP domain. Thus, bandwidth with modified dropback applied the dropback definition only in this area.

After defining bandwidth with modified dropback as in Table 24 the predictive metrics matched the following statistical mode of pilot ratings:

CAP—50% correlation

Bandwidth—50% correlation

Bandwidth with dropback—30% correlation

Bandwidth with modified dropback—70% correlation.

When CAP agreed with bandwidth with modified dropback there was a 67% prediction correlation. When bandwidth agreed with bandwidth with modified dropback there was a 63% correlation. Using the modified dropback, all predictive metrics agreed and matched pilot opinion for VSS configurations E and G. Configuration H was matched

by CAP and bandwidth with modified dropback. Bandwidth with modified dropback was the only metric which matched pilot opinion for configuration I. Both bandwidth and bandwidth with modified dropback predictions agreed and matched pilot opinion for configurations J and K.

Table 24 VSS Configurations' Handling Qualities Levels Summary

VSS Configuration	Mode of Actual Pilot Opinion	Predictive Metric			
		CAP	Bandwidth	Proposed Bandwidth with Dropback	Proposed Bandwidth with Modified Dropback[1]
A	3	2	2	2	2
C2	2	2	2	2	2
D	3	2	2	2	2
E	1	1	1	2	1
G	1	1	1	2	1
H	1	1	2	2	1
I	2	1	1	2	2
J	2	3	2	3	2
K	1, 2	1	2	3	2
P	3	1	2	3	2

Note: 1. Proposed bandwidth with modified dropback uses the proposed definition of bandwidth and applies the dropback definition only for VSS configurations which had a short period natural frequency greater than or equal to configuration I, or for configurations A, C2, D, and I.

As shown in Figure 29, VSS configuration H lay between the current bandwidth Level 1 boundary and the proposed bandwidth Level 1 boundary. If the modified dropback definition is applied, then configuration H is predicted to be Level 1 by bandwidth with modified dropback. Thus, this configuration supports the location of the proposed boundary. Decreasing the bandwidth to configuration K crosses the proposed boundary and agrees with pilot opinion as being a Level 1, Level 2 configuration. Thus, flight test results support the location of the proposed bandwidth with dropback Level 1 boundary.

Up to this point, areas of agreement and conflict were developed between the CAP, bandwidth, and bandwidth with dropback criteria. Using these results a flight test using VISTA was accomplished which obtained actual pilot opinion in areas of agreement and conflict. This flight test also revealed that application of the dropback criterion should not be done in the blind—it should only be applied in those areas where historical data show pilots not only notice excessive dropback, but are also influence by it. The last chapter will bring together the results of this research along with recommendations for further research.

VII. Conclusions and Recommendations

The overall objective of this thesis was to determine areas of agreement and conflict between the CAP and bandwidth criteria and to evaluate the advantage of including the dropback criterion with bandwidth. This objective was accomplished in two phases.

Phase I mapped the CAP domain onto the bandwidth and dropback spaces for typical F-16 and Learjet type aircraft. This mapping exposed areas of agreement and disagreement between the various metrics. It also showed areas where degraded pilot opinion should occur. During this mapping it was realized that a closed region in CAP did not necessarily map onto a closed region in bandwidth. Further analysis revealed this was the result of the non-analyticity of the domains.

Phase II obtained pilot opinion in the regions found during Phase I. Pilot opinion of the high frequency VSS configurations (A, C2 and D) were influenced by excessive dropback. Pilot comments characterized these configurations as having an initial quick response followed by a slow, sluggish steady-state response. Additionally, pilot comments stated the pitch attitude was sensitive while the flight path was considered sluggish. Pilot comments also indicated these configurations were not predictable. Collectively, these indicators of excessive dropback were the primary factors contributing to the Level 2 and Level 3 Cooper-Harper ratings.

Pilot comments with regard to the mid frequency VSS configurations (E, G, H and I) indicated the handling qualities were well defined and predictable. However, it was

within this region that the evaluation pilots noticed the first signs of excessive dropback and its relative influence on the handling qualities of the configuration.

Pilot comments did not indicate excessive dropback for the low frequency configurations (J, K and P) although the dropback definition predicted excessive dropback. Comments suggested the decrease in pilot opinion resulted from the slow response and resulting over control and pitch overshoots. This over control led to angle of attack excursions during the initial offset correction. As a result, the evaluation pilots had harder touchdowns because of a lack of pitch response in the flare.

During the flight test both the CAP criterion and the bandwidth criterion matched actual pilot opinion approximately 50% of the time. Incorporating the current definition of dropback to the bandwidth criterion decreased the prediction accuracy to approximately 30%.

Flight test results indicated excessive dropback may have influenced pilot opinion only at relatively high values of CAP or short period natural frequencies (ω_{sp}). Results from this flight test are not sufficient enough to determine the exact location where dropback should be applied. However, results do indicate pilot opinion began being influenced by excessive dropback between an ω_{sp} of 2.3 and 3.3 rad/sec and between a CAP value of 1.31 and 2.68/g*sec^2. Pilot opinion was not influenced by excessive dropback at lower ω_{sp} or CAP values due to the relatively slow overall response. Thus, applying the dropback definition to the bandwidth criterion in those regions where pilot opinion was influenced by excessive dropback increased the prediction correlation to approximately 70%.

The following recommendations are made from the results of this research. They are made in the order the author feels to be most beneficial to the flying qualities community.

1. Compare the quantitative and qualitative flight test data to historical data. This comparison should help refine the level boundaries on the various criteria listed in MIL-STD-1797A.

2. Incorporate the modified dropback criterion with the bandwidth definition. However, further research needs to be accomplished determining where pilots are influenced by excessive dropback and downgrade an aircraft's handling qualities because of it. Additional research is also required in the area of the dropback flight test technique—excessive pitch attitudes encountered during the flight test caused the airspeed to significantly deviate off trim conditions, especially for the low frequency VSS configurations. Realize also that it will not be possible to have a computer generated boxcar input into the flight control system for most aircraft causing further spreads in the data.

3. Map all flying qualities criteria in MIL-STD-1797A onto one another showing regions of agreement and conflict. With these mappings, use flight test results to determine handling qualities trends within these regions.

4. As stated in Chapter 5, a handling qualities during tracking (HQDT) task was accomplished as a safety build-up for those VSS configurations predicted to be

Level 3. Use these flight test results to determine the adequacy of modeling a landing task with an HQDT task.

5. Map the CAP domain onto the bandwidth with modified dropback space. Compare these mapped regions to those presented in this research and to actual pilot opinion.

6. Map the CAP domain onto the bandwidth and dropback criteria using the phugoid, actuator and stick dynamics of VISTA. Compare these mapped regions to where the VSS configurations lay and to actual pilot opinion.

7. As shown in Figure 16, there were two areas in the CAP domain where a potential existed for a discontinuity in the bandwidth space. This research mapped out a jump line in the upper left region. Determine if a jump line exists in the lower left region and whether pilot opinion should degrade as this region is approached.

Appendix A

Pilot Rating Scales

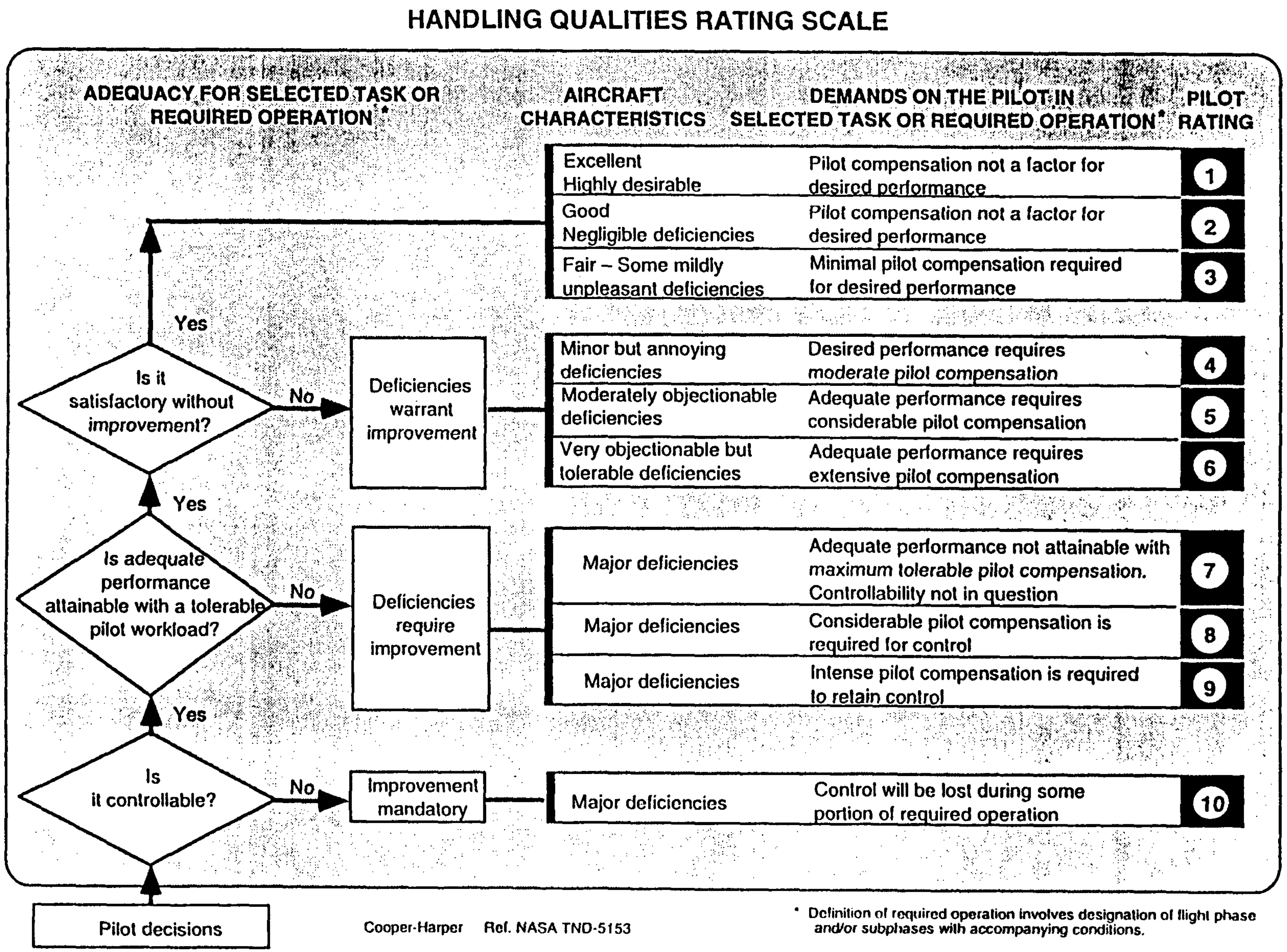


Figure 33 Cooper-Harper Pilot Rating Scale

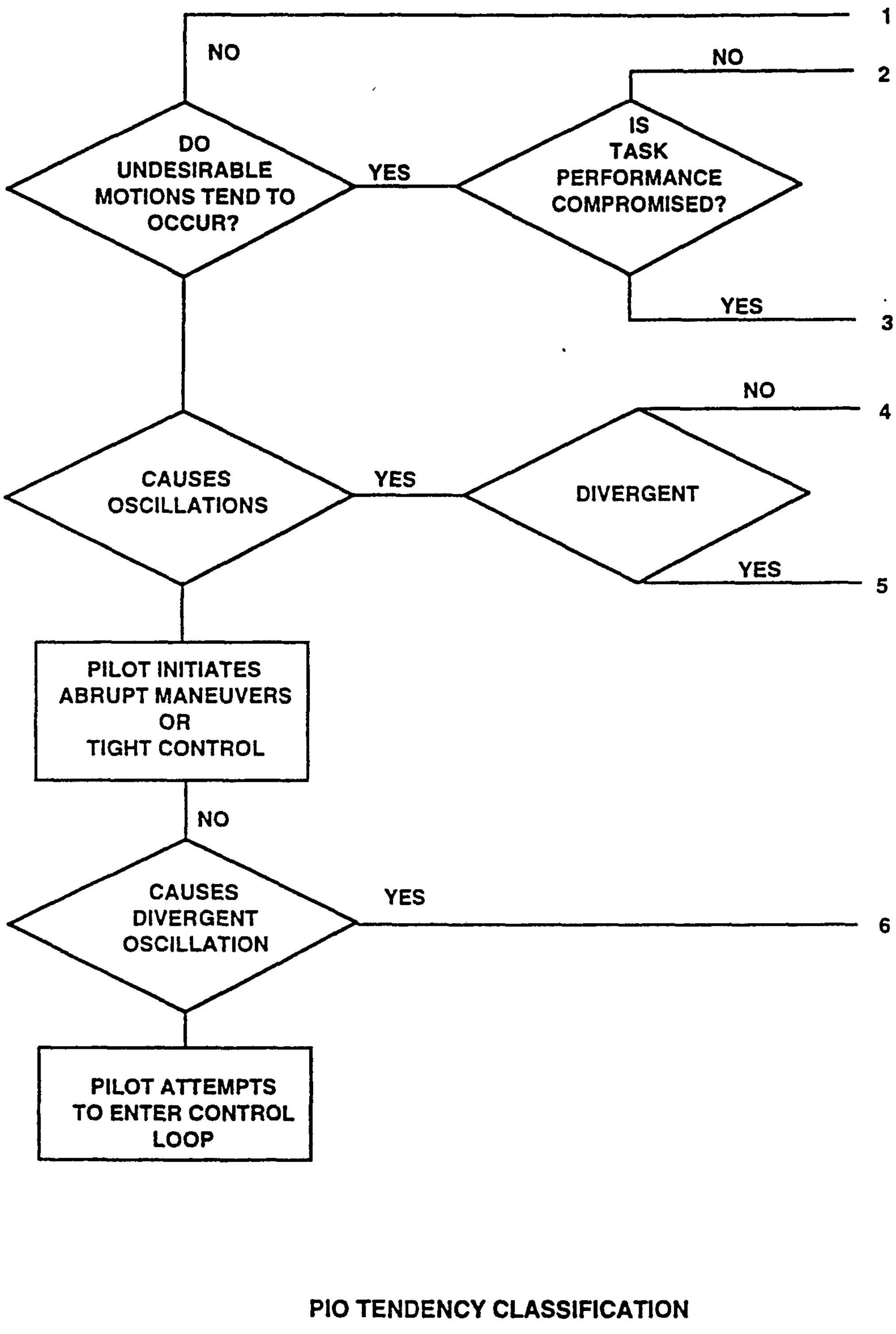


Figure 34 Pilot Induced Oscillation Rating Scale

Appendix B

Learjet Results

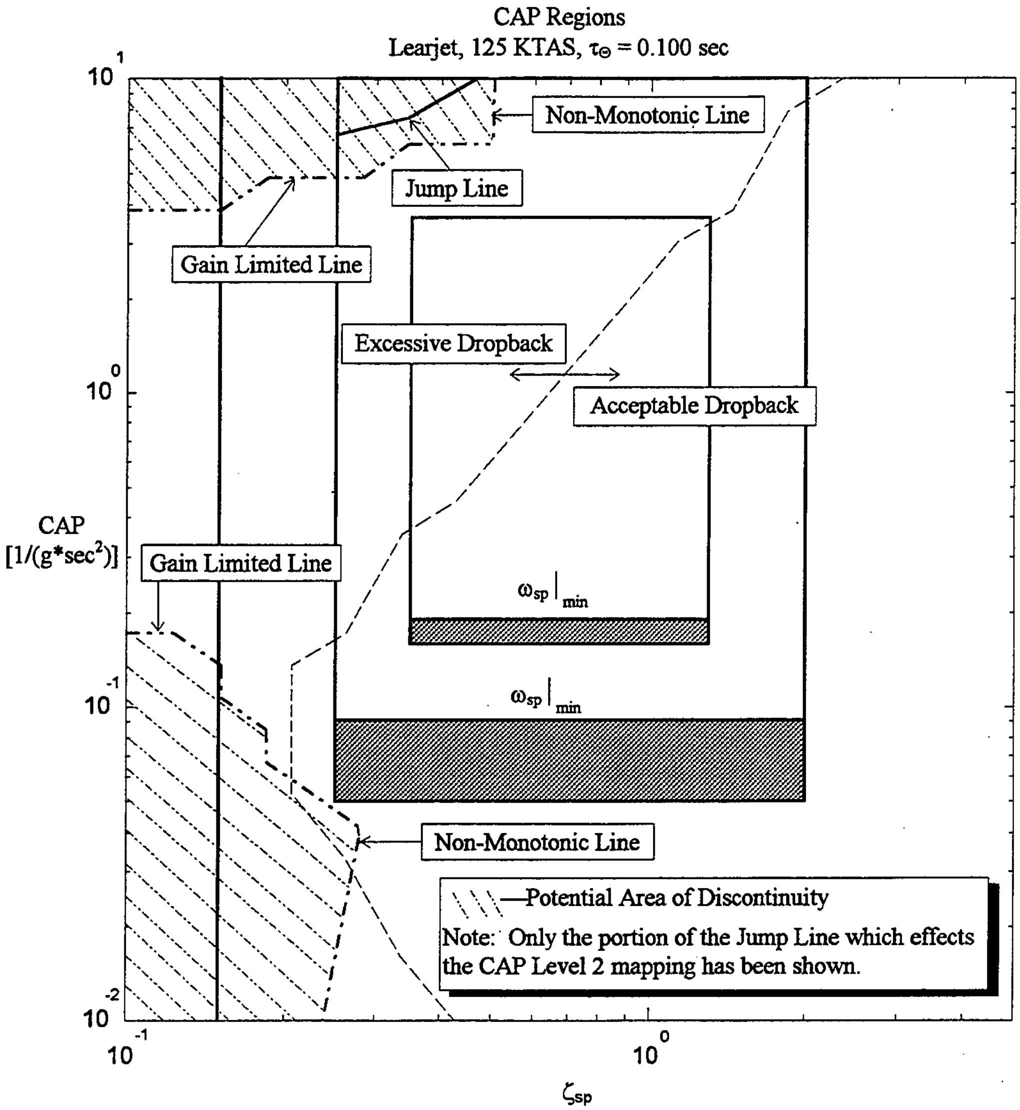


Figure 35 Composite View of the CAP Space (Learjet)

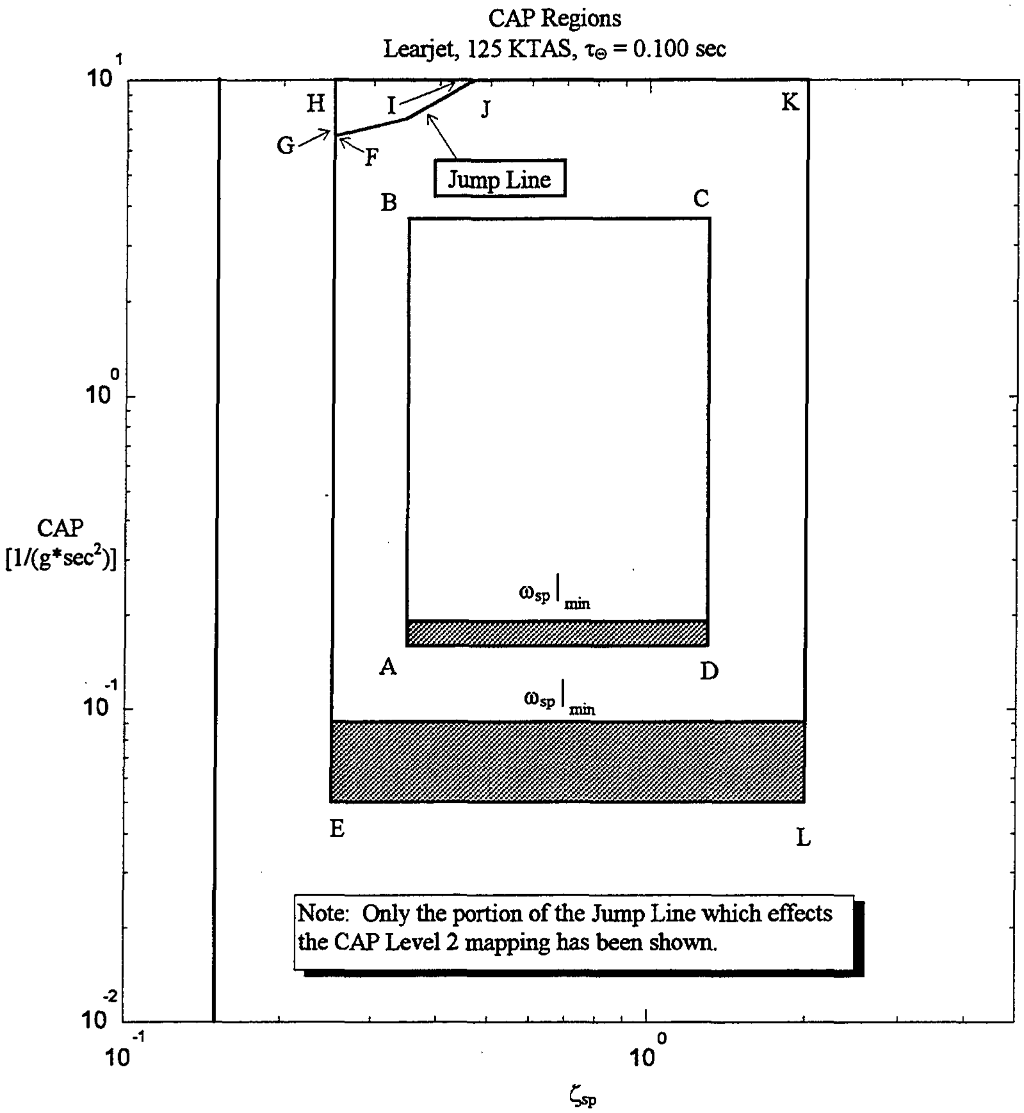


Figure 36 Area Map of CAP (Learjet)

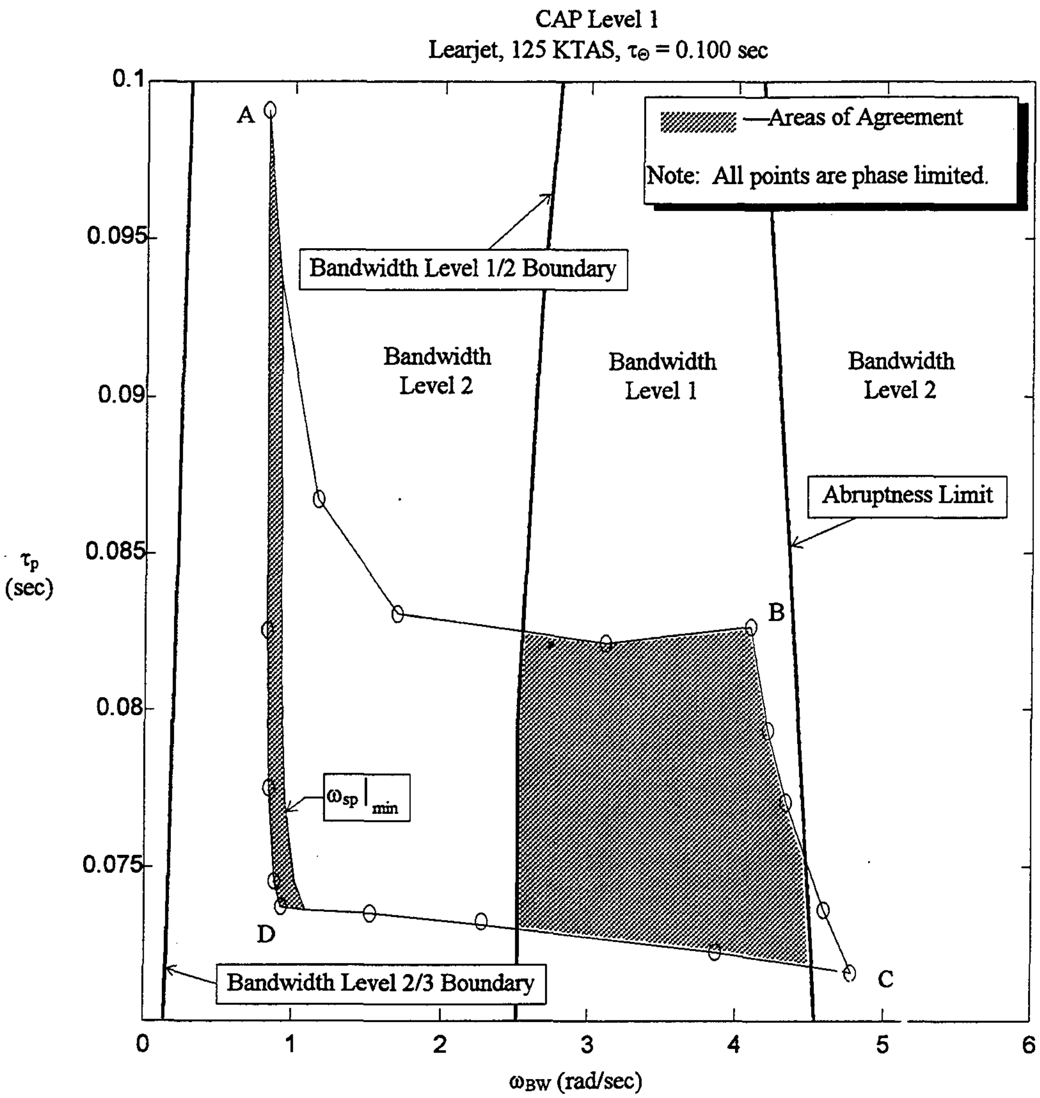


Figure 37 CAP Level 1 Mapped onto the Bandwidth Criterion (Learjet)

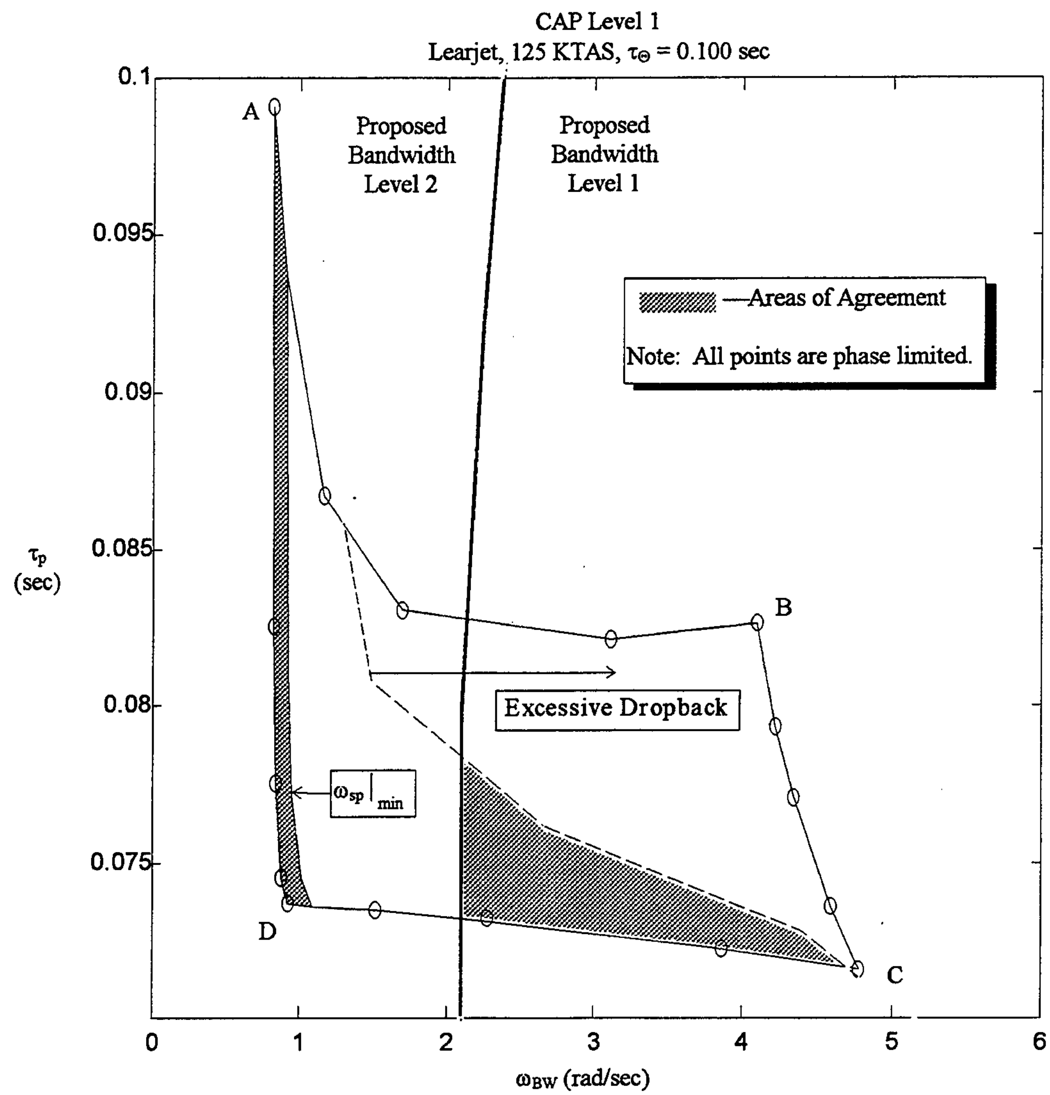


Figure 38 CAP Level 1 Mapped onto the Proposed Bandwidth with Dropback Criterion (Learjet)

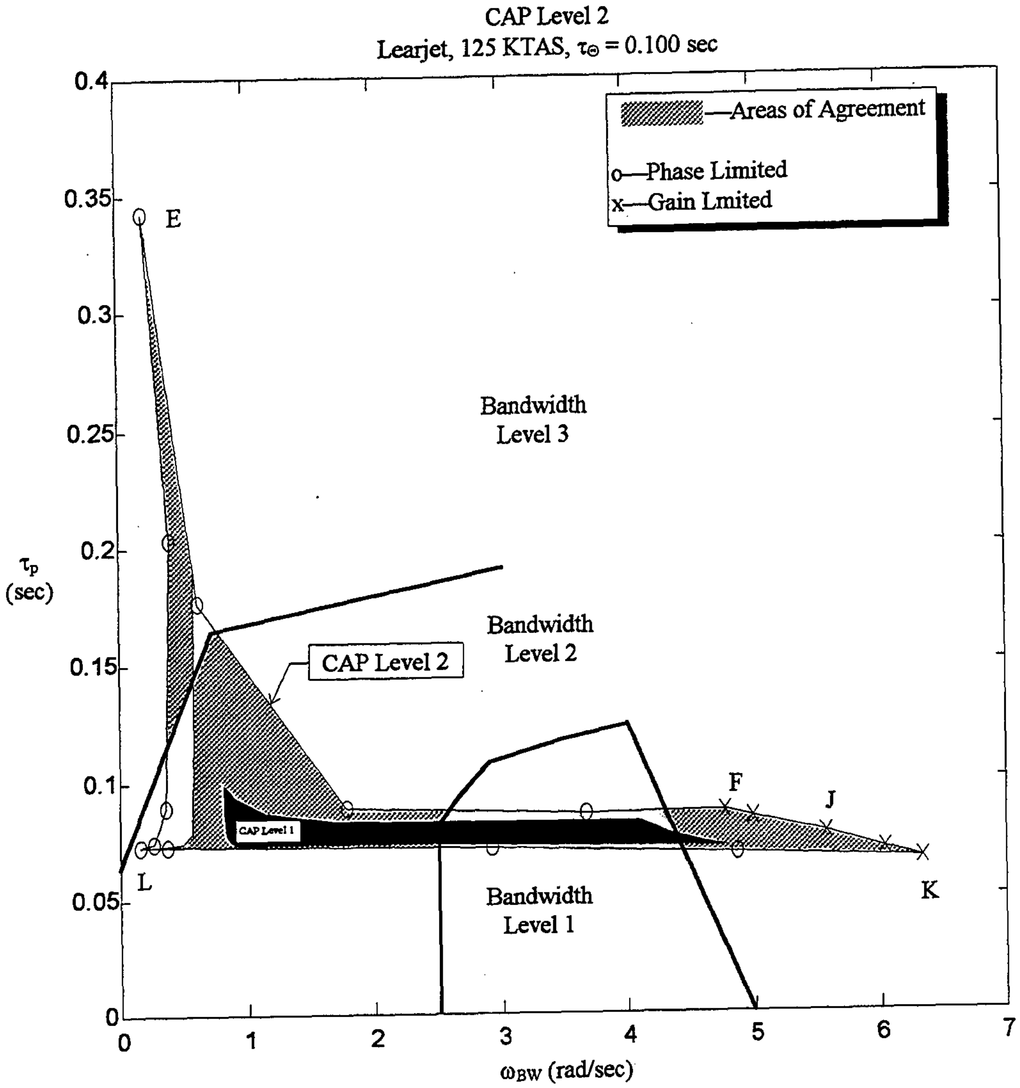


Figure 39 CAP Level 2 Mapped onto the Bandwidth Criterion (Learjet)

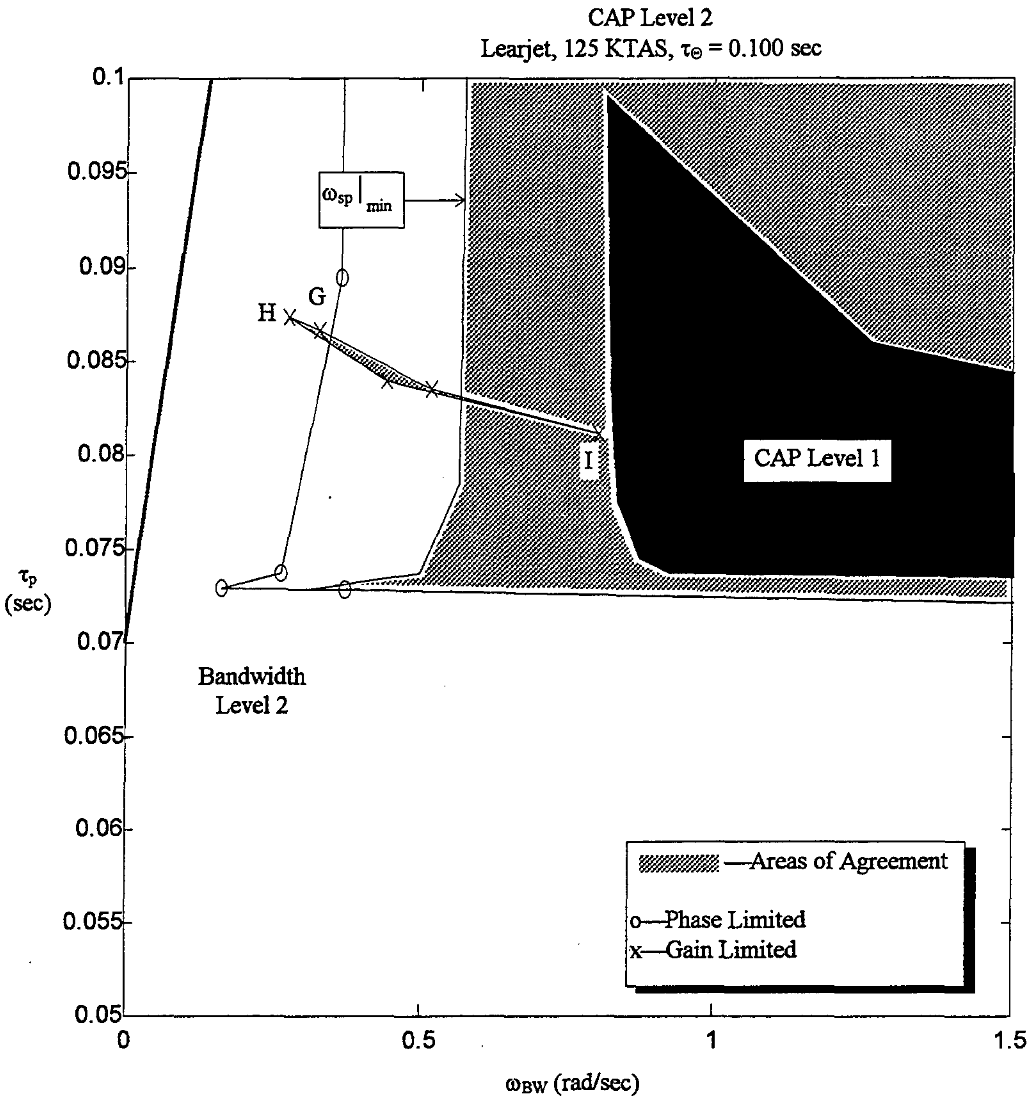


Figure 40 CAP Level 2 Mapped onto the Bandwidth Criterion—Jump Area (Learjet)

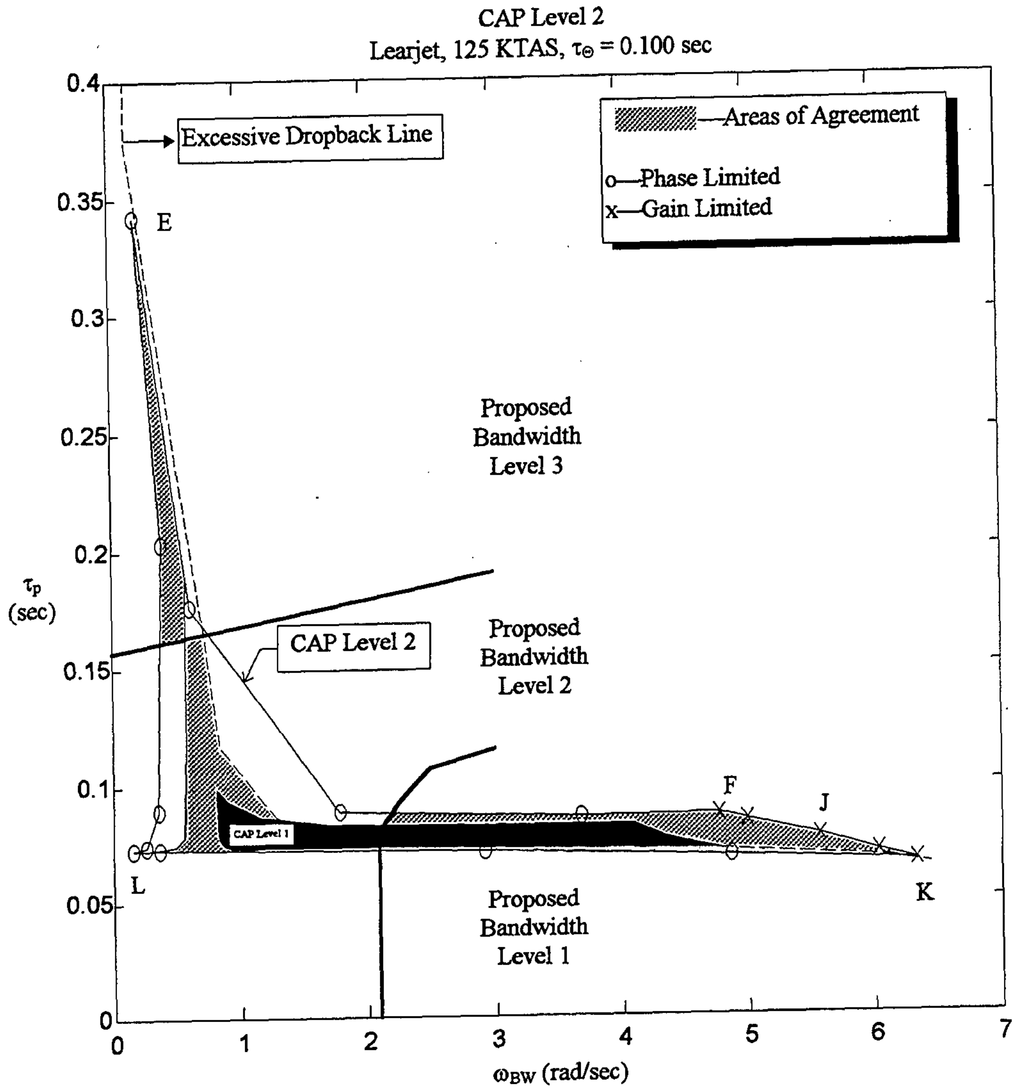


Figure 41 CAP Level 2 Mapped onto the Proposed Bandwidth with Dropback Criterion (Learjet)

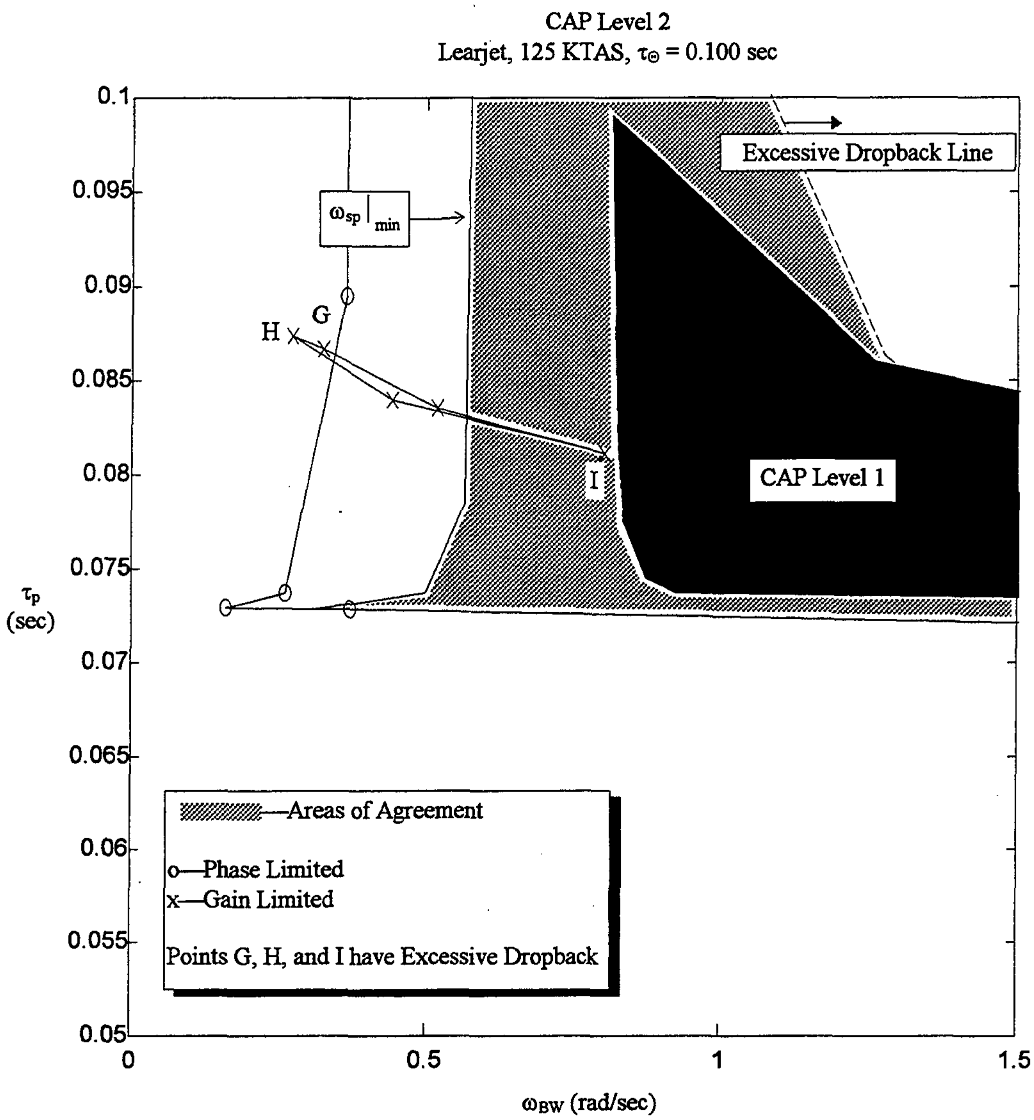
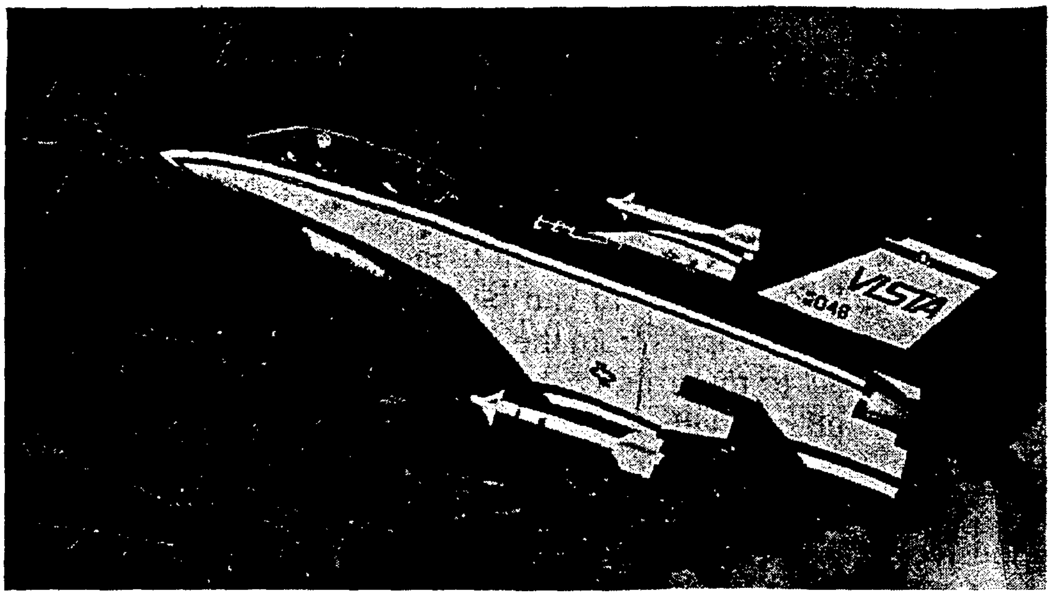


Figure 42 CAP Level 2 Mapped onto the Proposed Bandwidth with Dropback Criterion—Jump Area (Learjet)

Appendix C

VISTA Description



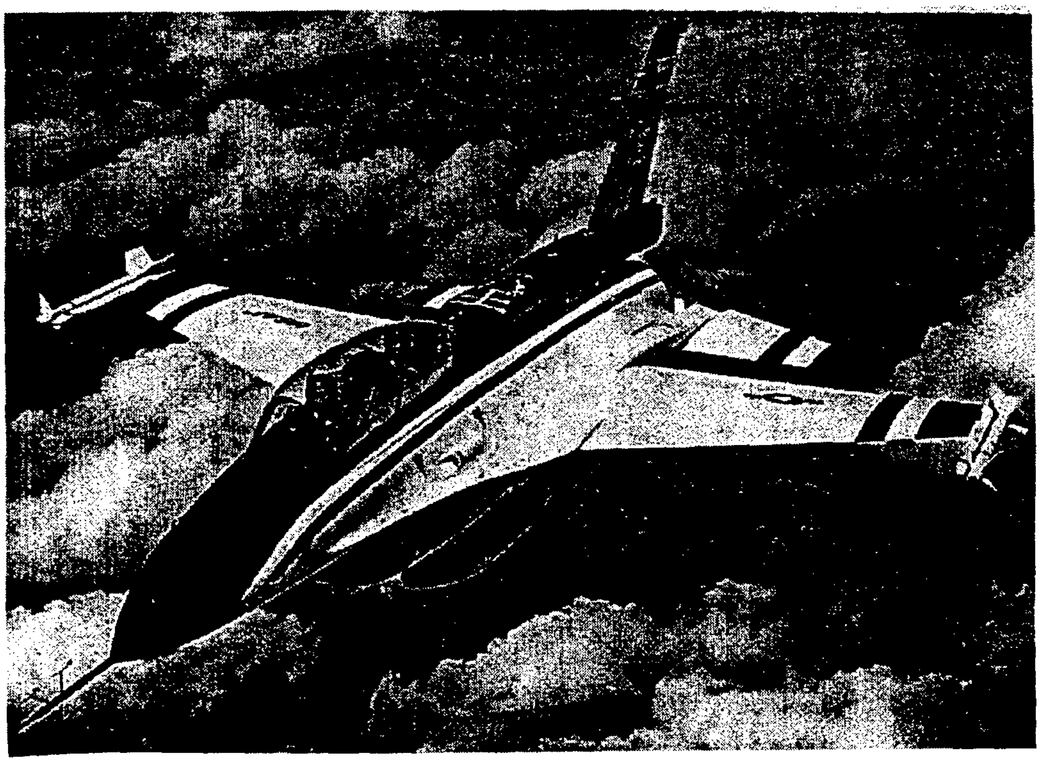


Figure 43 VISTA Illustration

Designed for Future Growth

VISTA's robust design allows for future growth and expanding technology. Provisions currently exist for:

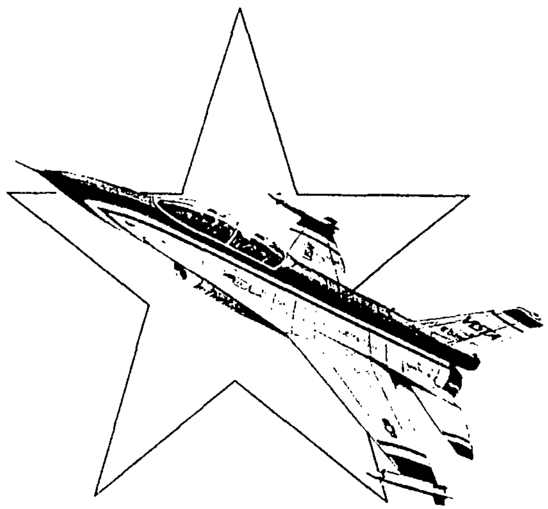
- Higher Fidelity Simulation
- Model Following
- Supersonic Simulation Envelope
- Full Six Degrees of Freedom
- Tactile Queing
- Variable Feel Side Stick
- Programmable Displays

Today's VISTA program offers state-of-the-art in-flight simulation from a recognized leader in the field. It gives a high performance/low cost answer to aircraft systems testing while minimizing risk and accommodating program schedule. For more information on this dynamic in-flight simulator, please contact:

Dave Frearson
VISTA Program Manager
In-Flight Simulation Group

Phone: (513) 255-8276
Mail: WRDC/FIGX
Wright Patterson AFB, OH 45433-6553

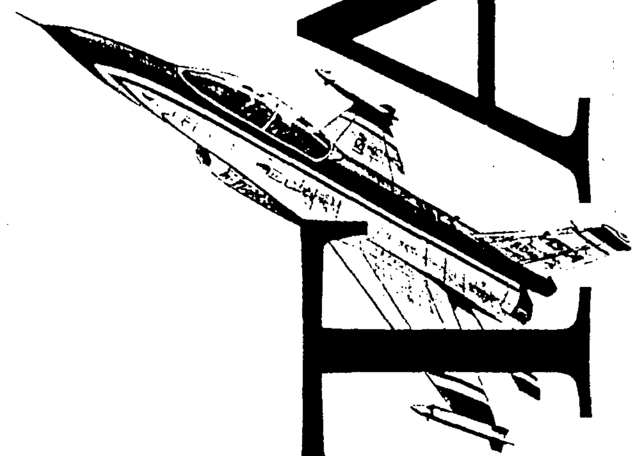
WHY VISTA IN-FLIGHT SIMULATION?



- **Lower Cost** - No hardware to build.
- **Lower Risk** - Software simulation before actual test flight.
- **Greater Flexibility** - Ability to fly several aircraft configurations using one airframe.
- **Short Schedule** - Highly responsive to customer needs.
- **Independent Agent (CALSPAN)** - Good reputation and past experience.

EXPLORE BEYOND TODAY'S HORIZONS WITH ***VISTA***

VISTA



The Premier
High Performance
In-Flight
Simulator

What Is VISTA?

VISTA is a new, high performance in-flight simulator currently being developed by the U.S. Air Force to support aeronautical research and development over the next 25 years. The Variable Stability In-flight Simulator Aircraft (VISTA) uses the F-16D as its host aircraft.

VISTA's primary mission is to simulate the flight characteristics and pilot interfaces of new flight vehicles and advanced weapons systems. When complete, VISTA will offer significant increases in performance over existing in-flight simulators, including the ability to simulate a wider range of aircraft dynamics.

Why Use VISTA?

Since VISTA is an actual aircraft whose cockpit environment can be changed to match that of another aircraft, it provides a degree of realism not present in ground simulation. As the pilot moves the controls, he experiences the real flight motions, accelerations, and handling qualities of the simulated aircraft. This realism gives the pilot a higher level of confidence in the results.

High Performance Features

VISTA will be available for use in 1992. Its modern F-16D fighter host aircraft will contain full instrumentation and will possess many high performance features:

- High Thrust-to-Weight Ratio
- Variable Feel Center Stick Controlled by Dedicated Digital Computer
- Control of Five Degrees of Freedom
- Response Feedback Variable Stability System (VSS)
- Direct Lift Control
- Heavy Duty Landing Gear
- Additional Space in the Dorsal Fairing for Customer Hardware
- Two Hard Points To Attach a Pod
- Data Recording Systems Capable of Recording 400 Digital and Analog Parameters at 200 samples/sec

In addition, VISTA will be able to record pilot comments and evaluate both cockpit Multi-Function Displays (MFDs) and the Heads-Up Display (HUD) on video recorders. The on-aircraft ground simulation capability will exercise the entire VSS system with the exception of the VSS sensors and the HUD.

Simulation Capabilities

The VISTA aircraft will offer a substantial increase in performance over existing in-flight simulators. Most significant will be its ability to simulate a wider range of aircraft dynamics. Parameters for the aircraft's minimum handling qualities as well as its dynamic operating envelope are given below.

<u>Handling Quality:</u>

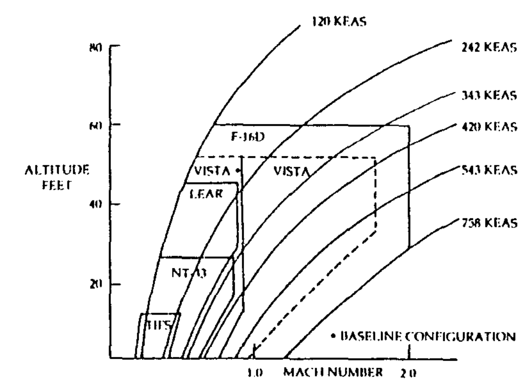
Short Period Natural Freq.	0 to 12 rad/sec
Short Period Damping	-0.1 to 1.1
Nz/alpha	1 to 100g/rad
Stick Force/g	1 to 200lbs/g
Phugoid Natural Freq.	0 to .5 rad/sec
Phugioid Damping	-0.3 to 1.0
Dutch Roll Natural Freq.	2 to 8 rad/sec
Dutch Roll Damping	-0.1 to 1.0
Roll/Spiral Mode Natural Freq.	0 to 5 rad/sec
Roll/Spiral Mode Damping	-0.1 to 1.0
Roll/Sideslip Φ/β	0 to 10
Variable Time Delay	0.01 to 0.5 sec
Lead/Lag	1 to 63 rad/sec

<u>Operating Envelope:</u>

Sideslip	+/-10 degrees
Side Acceleration	+/-0.5g
Landing Speed	130-160 Kts
Direct Lift	+/-1g
Pitch Pointing	+/-7deg Delta Alpha
Normal Accel g's	-2.4/+7.33

A comparison between VISTA and existing U.S. in-flight simulators clearly illustrates VISTA's superiority.

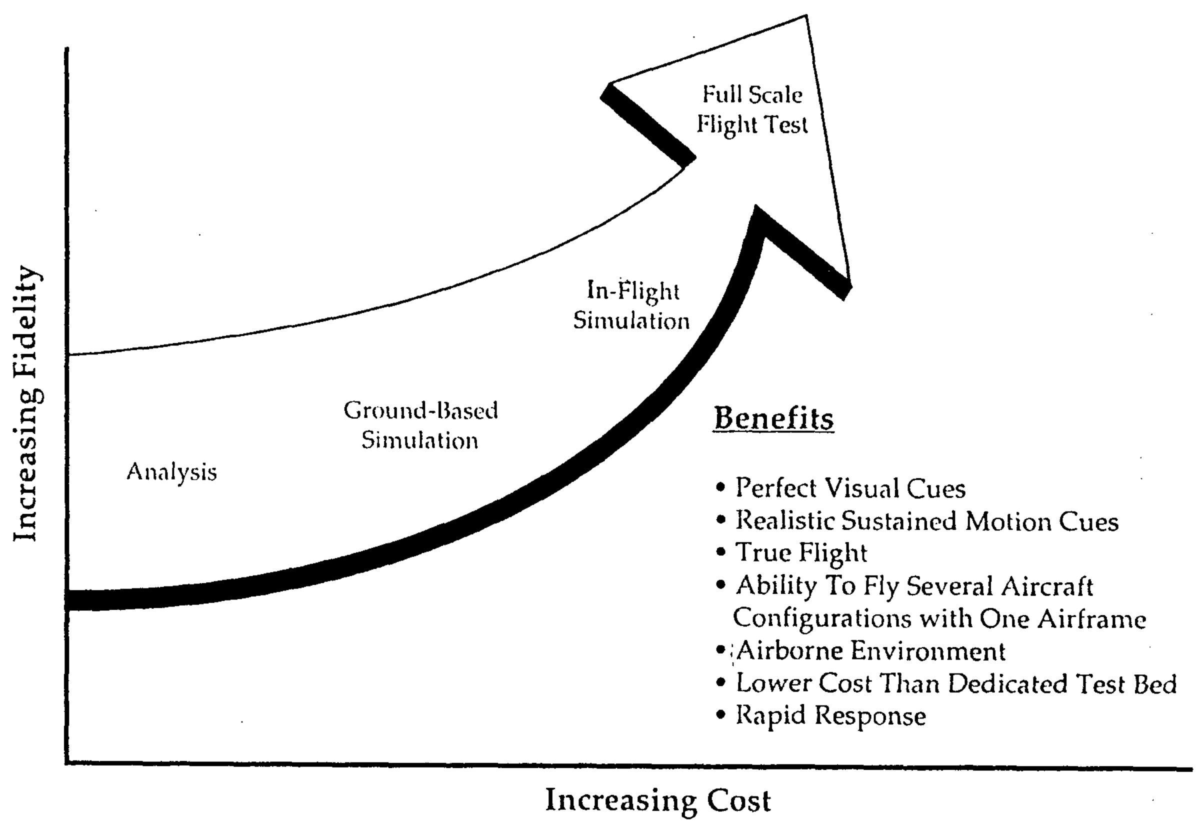
SIMULATION ENVELOPE



In addition, VISTA has been specifically designed to achieve very fast pitch and roll rates. The mechanical flow restrictors on the Integrated Servo Actuators (ISAs) will be replaced by command limiters in the flight control computer. This will increase the deflection rates of the control surfaces, thereby quickening angular acceleration response. The planned aircraft angular accelerations are:

Roll Acceleration	6.0 rad/s ^{2} in 0.8g sec
Pitch Acceleration	1.0 rad/s ^{2} in 0.4g sec
Yaw Acceleration	0.44 rad/s ^{2} in 0.27g sec

VISTA Also Offers the Twin Advantages of Flexibility and Safety Over Full Scale Flight Testing.



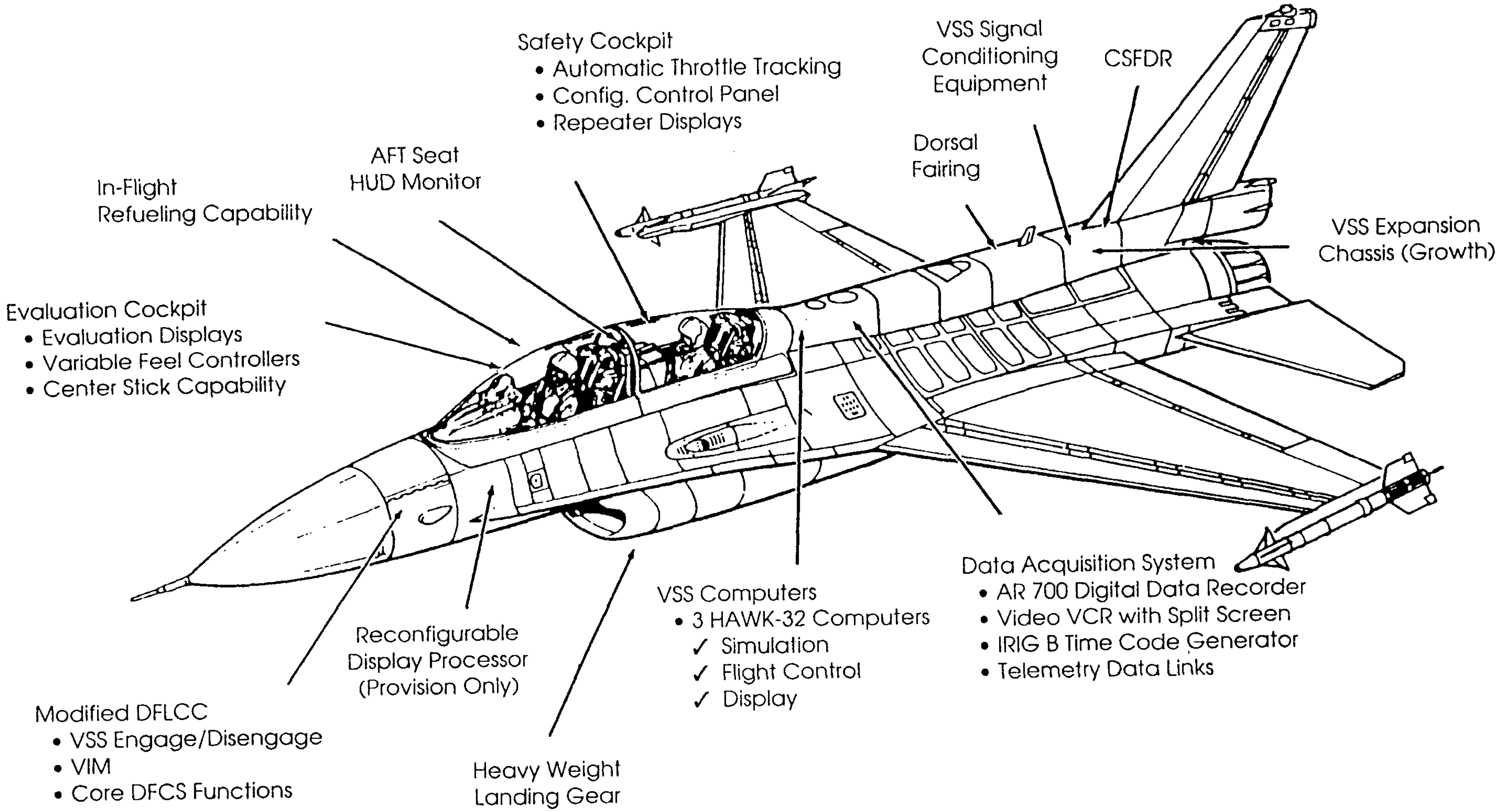


Figure 44 VISTA Component Layout

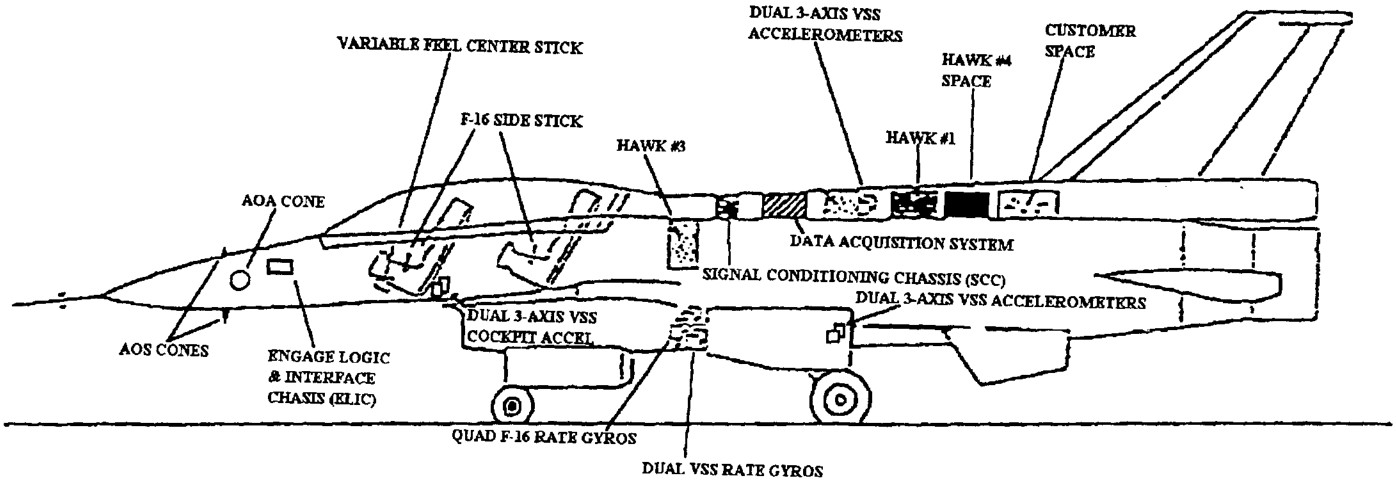


Figure 45 VISTA Component Layout Concluded

Appendix D

Flight Test Data Plots

Test Aircraft: VISTA - NF-16D
Date: 17 Sep 95
Configuration: Gear - DOWN, Speed Brake - OUT
Data Source: Data Acquisition System (20 Hertz)
Outside Air Temperature: 83°F
Pressure Altitude: 2,211 feet

Maneuver: Lateral Offset Landing Task
VSS Configuration: A - 172
Pilot: 4
Test Point: 6.4
Aircraft Weight: 25,500 pounds

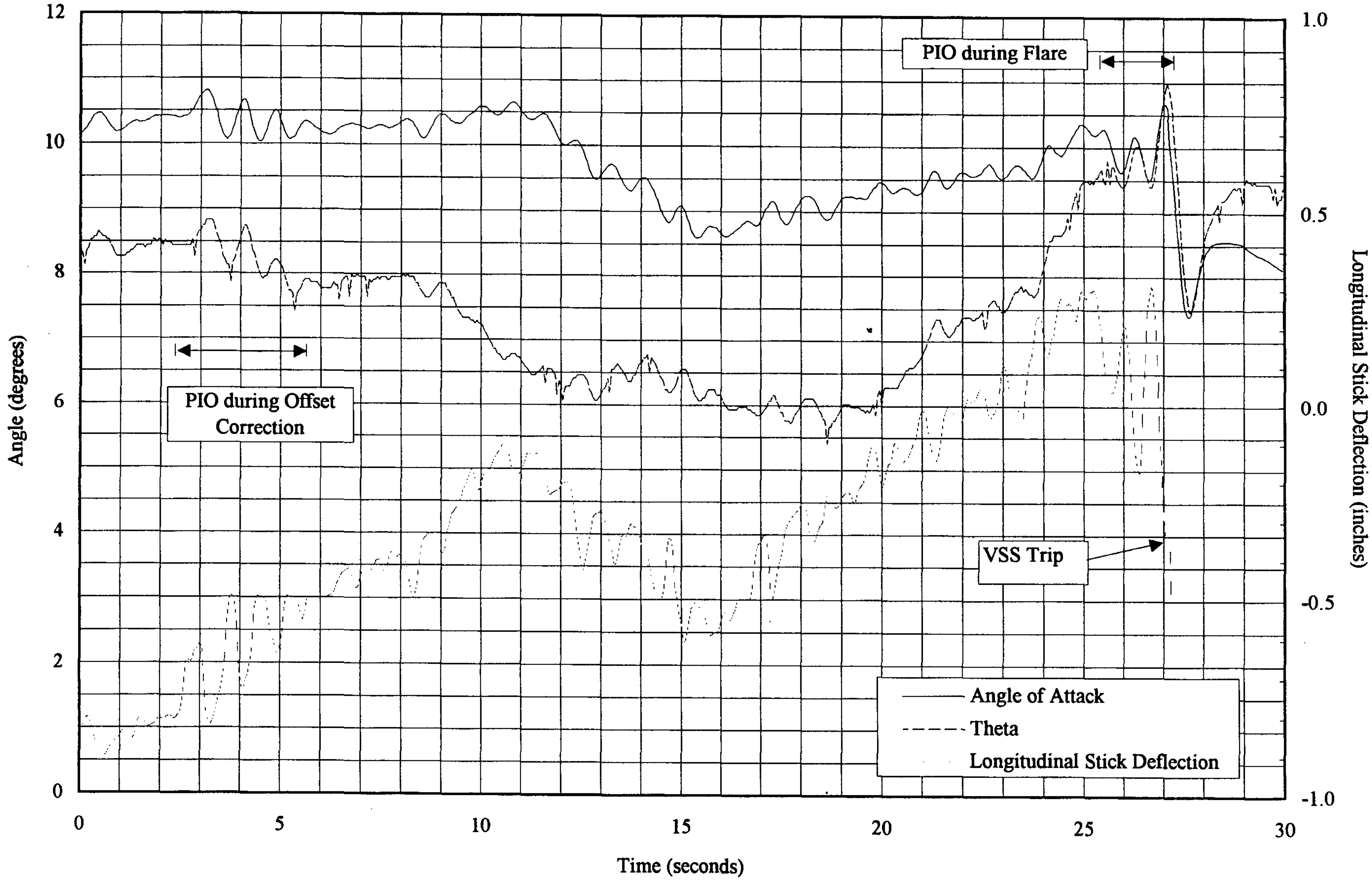


Figure 46 Longitudinal Stick Deflection Time Trace During PIO

Test Aircraft: VISTA - NF-16D
Date: 17 Sep 95
Configuration: Gear - DOWN, Speed Brake - OUT
Data Source: Data Acquisition System (20 Hertz)
Outside Air Temperature: 83°F
Pressure Altitude: 2,211 feet

Maneuver: Lateral Offset Landing Task
VSS Configuration: A - 172
Pilot: 4
Test Point: 6.4
Aircraft Weight: 25,500 pounds

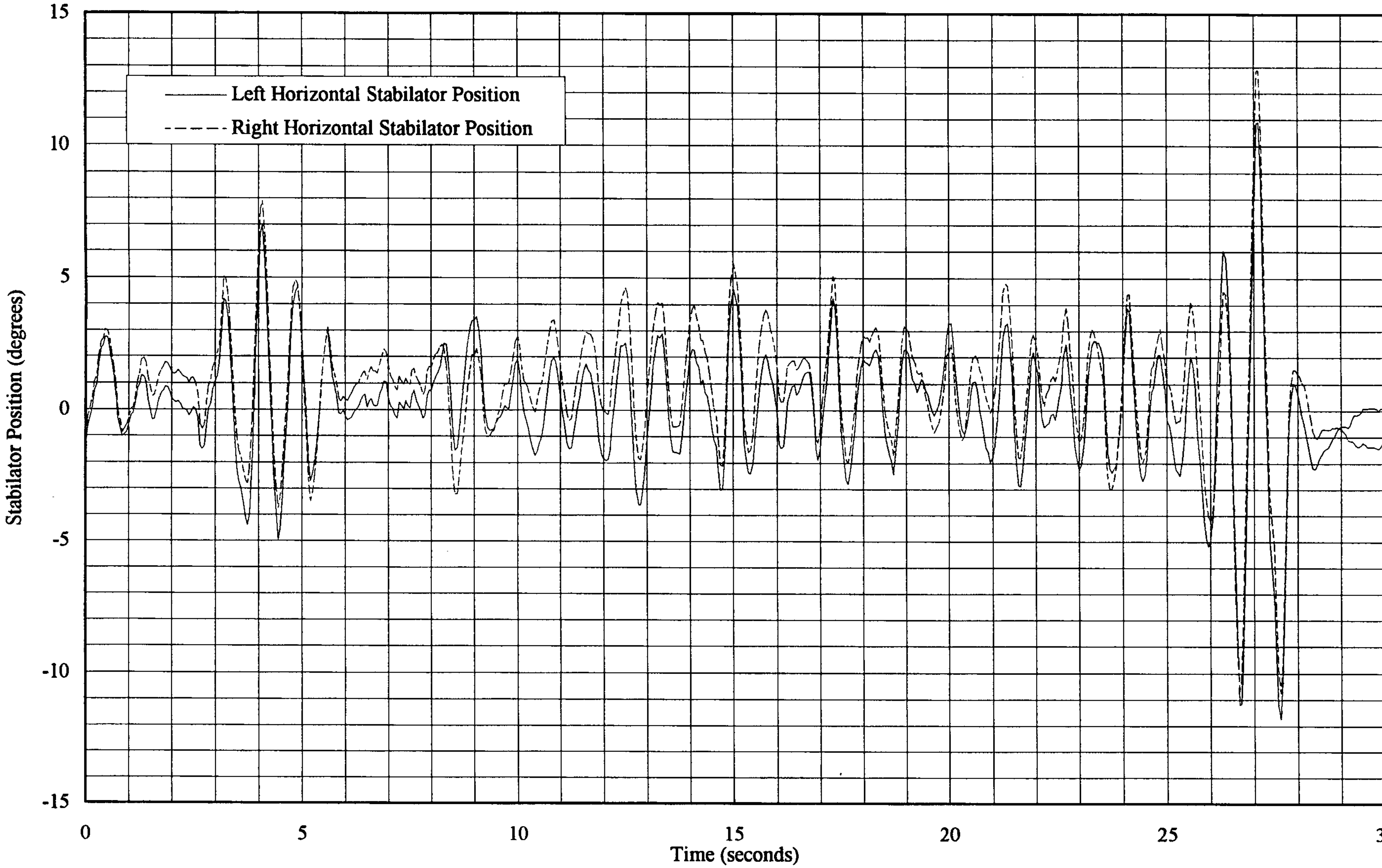


Figure 47 Stabilator Position Time Trace During PIO

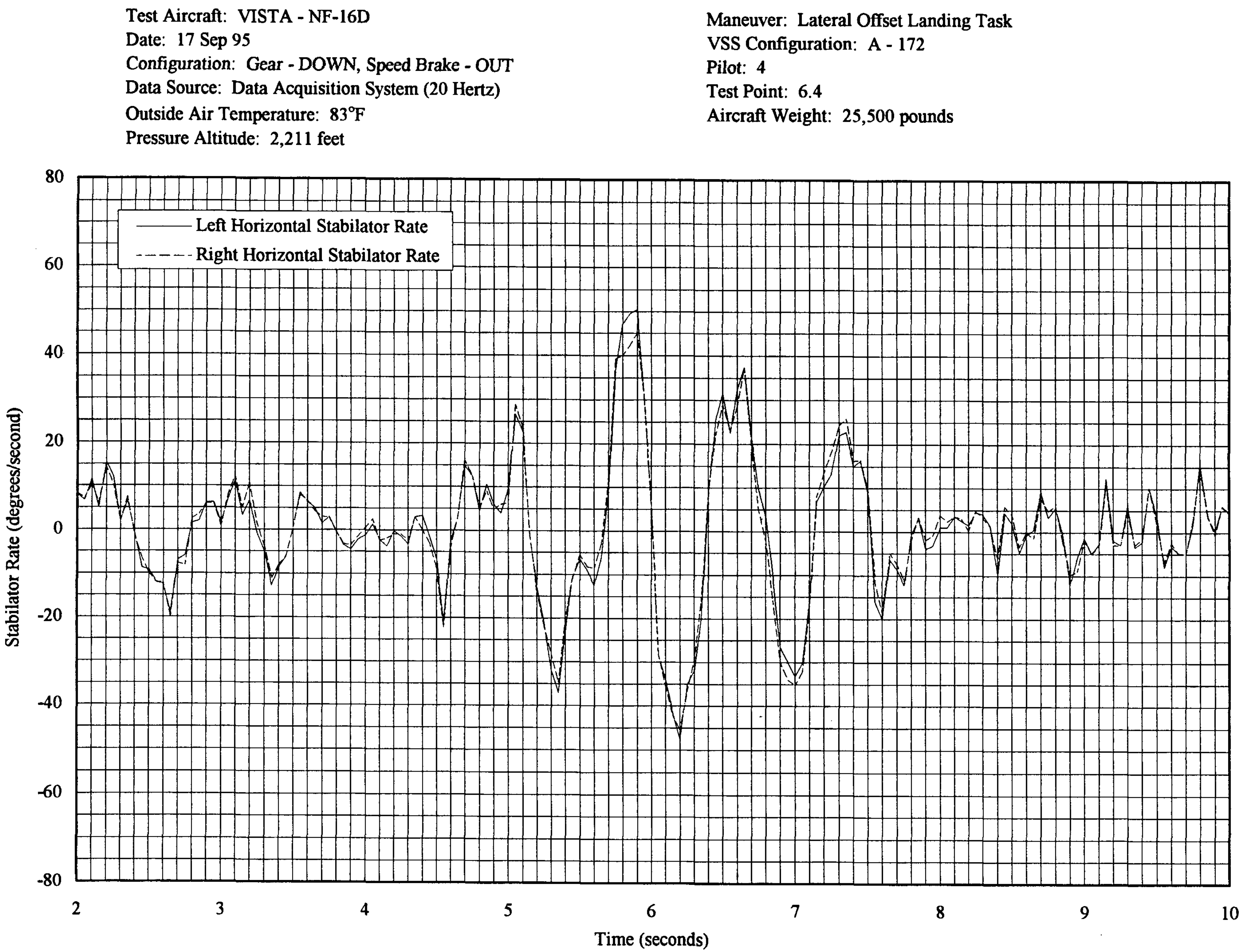


Figure 48 Stabilator Rate Time Trace During Offset Correction

Test Aircraft: VISTA - NF-16D
Date: 17 Sep 95
Configuration: Gear - DOWN, Speed Brake - OUT
Data Source: Data Acquisition System (20 Hertz)
Outside Air Temperature: 83°F
Pressure Altitude: 2,211 feet

Maneuver: Lateral Offset Landing Task
VSS Configuration: A - 172
Pilot: 4
Test Point: 6.4
Aircraft Weight: 25,500 pounds

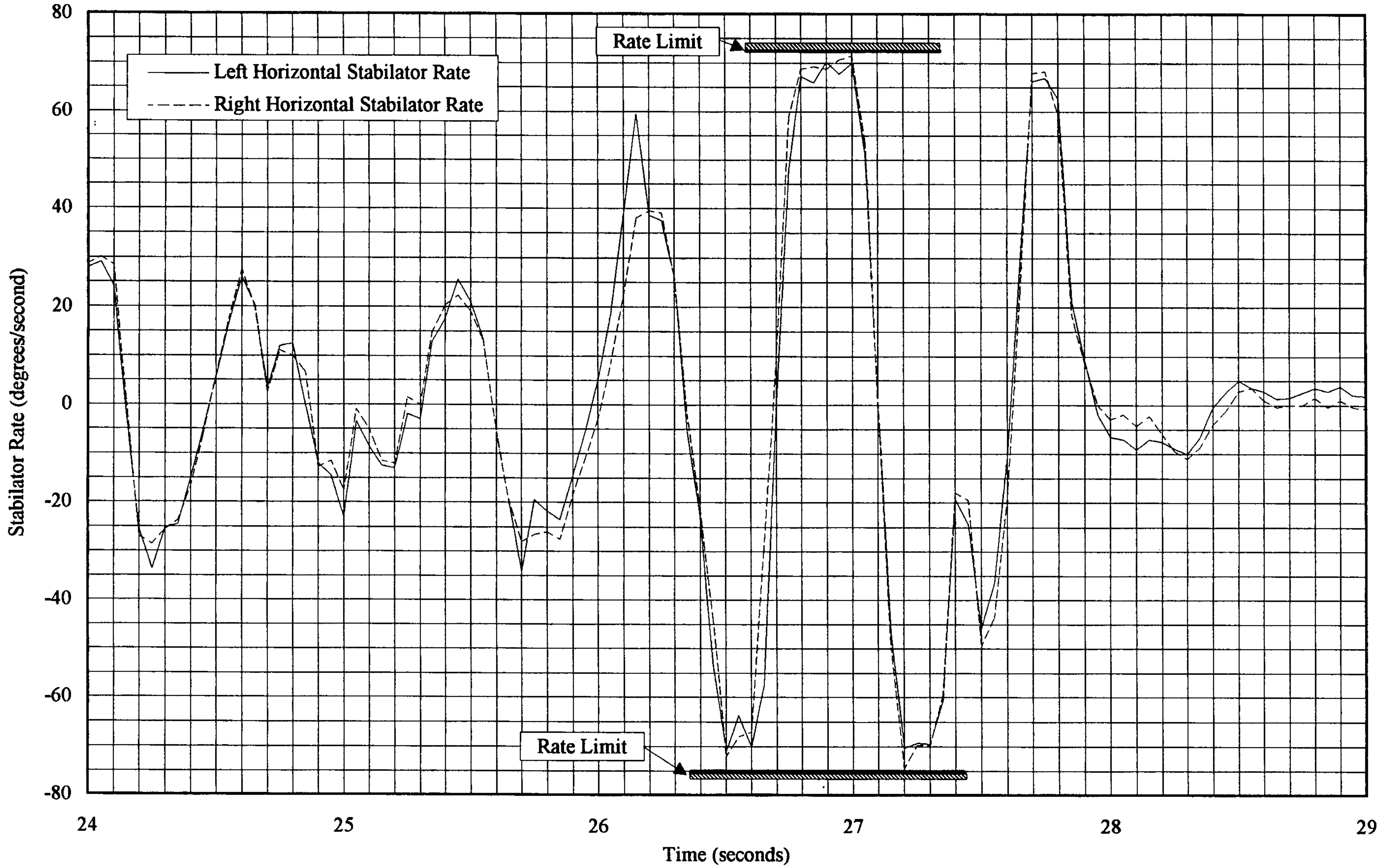


Figure 49 Stabilator Rate Time Trace During Flare

Appendix E

Jump Line Development

Jump Line Development

As developed in Chapter 3, the governing equations for ω_{BW_G} were non-linear, transcendental equations. However, ω_{BW_G} may be solved for numerically using various techniques. The technique used in this research was a modified version of Newton's method (25:454-464). To utilize this method, it was necessary to select a ζ_{sp} and to subtract the right hand side of Equation 18 from both sides resulting in

$$F(\omega_{BW_G}, \omega_{sp}, \omega_{180}(\omega_{sp})) = 0. \tag{37}$$

Note that by specifying ζ_{sp}, F became a function of only ω_{BW_G} and ω_{sp}. Due to the fact that ω_{180} could not explicitly be substituted into Equation 37, its dependency on F has been shown to aid in the following development.

The first step in this modified version of Newton's method was to determine a solution of Equation 37, designated as $\omega_{BW_G}^*$ and ω_{sp}^*. The frequency where the Bode phase plot equaled -180°, ω_{180}, was found given ζ_{sp} and ω_{sp}^* satisfying Equation 17. With this solution, Equation 37 was re-written as

$$F^*(\omega_{BW_G}^*, \omega_{sp}^*, \omega_{180}^*(\omega_{sp}^*)) = 0. \tag{38}$$

The next step was to propagate the function by either stepping in ω_{BW_G} or ω_{sp} by letting

$$\omega_{BW_G} = \omega_{BW_G}^{*} + \Delta\omega_{BW_G} \tag{39}$$

or

$$\omega_{sp} = \omega_{sp}^{*} + \Delta\omega_{sp}, \tag{40}$$

where $\Delta(\cdot)$ indicates the step size and direction. It will be shown later the determination of stepping in ω_{BW_G} or ω_{sp} depended upon the magnitude of $\frac{\partial F}{\partial \omega_{BW_G}}$ and $\frac{\partial F}{\partial \omega_{sp}}$, and the direction of the step depended upon the sign of $\frac{\partial F}{\partial \omega_{BW_G}}$ and $\frac{\partial F}{\partial \omega_{sp}}$. For the sake of illustration, assume a starting step in ω_{sp} as shown in Figure 50.

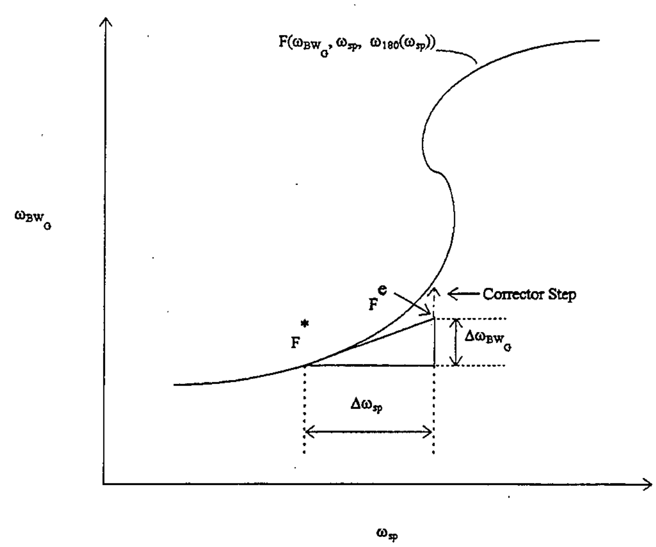


Figure 50 Illustration of the Modified Newton's Method

An estimate of F, F^e, was calculated by expanding Equation 37 about $(\cdot)^*$ using a first order Taylor Series approximation, or

$$F^e(\omega_{BW_G}, \omega_{sp}, \omega_{180}(\omega_{sp})) = F^*(\omega_{BW_G}{}^*, \omega_{sp}{}^*, \omega_{180}{}^*(\omega_{sp}{}^*)) +$$

$$+\frac{\partial F}{\partial \omega_{BW_G}}\Delta\omega_{BW_G} + \frac{\partial F}{\partial \omega_{sp}}\Delta\omega_{sp} + \frac{\partial F}{\partial \omega_{180}}\cdot\frac{\partial \omega_{180}}{\partial \omega_{sp}}\Delta\omega_{sp} + O[\Delta^2], \qquad (41)$$

where $O[\Delta^2]$ represents the order of the higher order terms—a function of $\Delta\omega_{BW_G}{}^2$ and $\Delta\omega_{sp}{}^2$. The partials of F were:

$$\frac{\partial F}{\partial \omega_{BW_G}} = -\frac{\omega_{BW_G}}{\omega_{BW_G}^2 + 1/T_{\Theta_2}} + \frac{1}{\omega_{BW_G}} + \frac{4\zeta_{sp}^2\omega_{sp}^2\omega_{BW_G} - 2\omega_{BW_G}\left(\omega_{sp}^2 - \omega_{BW_G}^2\right)}{\left(\omega_{sp}^2 - \omega_{BW_G}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{BW_G}^2}, \quad (42)$$

$$\frac{\partial F}{\partial \omega_{sp}} = \frac{2\omega_{sp}\left(\omega_{sp}^2 - \omega_{BW_G}^2\right) + 4\zeta_{sp}^2\omega_{sp}\omega_{BW_G}^2}{\left(\omega_{sp}^2 - \omega_{BW_G}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{BW_G}^2} - \frac{2\omega_{sp}\left(\omega_{sp}^2 - \omega_{180}^2\right) + 4\zeta_{sp}^2\omega_{sp}\omega_{180}^2}{\left(\omega_{sp}^2 - \omega_{180}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{180}^2}, \quad (43)$$

$$\frac{\partial F}{\partial \omega_{180}} = \frac{\omega_{180}}{\omega_{180}^2 + 1/T_{\Theta_2}} - \frac{1}{\omega_{180}} - \frac{4\zeta_{sp}^2\omega_{sp}^2\omega_{180} - 2\omega_{180}\left(\omega_{sp}^2 - \omega_{180}^2\right)}{\left(\omega_{sp}^2 - \omega_{180}^2\right)^2 + 4\zeta_{sp}^2\omega_{sp}^2\omega_{180}^2}. \qquad (44)$$

By taking the partial of Equation 17 with respect to ω_{sp} and through algebraic simplification

$$\frac{\partial\omega_{180}}{\partial\omega_{sp}} = \frac{2\zeta_{sp}\omega_{180} - \dfrac{4\zeta_{sp}\omega_{sp}^2\omega_{180}}{\omega_{sp}^2 - \omega_{180}^2}}{\dfrac{T_{\Theta_2}D}{1+T_{\Theta_2}\omega_{180}} - \tau_{\Theta}D - 2\zeta_{sp}\omega_{sp} - \dfrac{4\zeta_{sp}\omega_{sp}\omega_{180}^2}{\omega_{sp}^2 - \omega_{180}^2}}, \tag{45}$$

where

$$D = \omega_{sp}^2 - \omega_{180}^2 + 2\zeta_{sp}\omega_{sp}\omega_{180}. \tag{46}$$

From Equation 37, not only should F^* equal zero but F^c should equal zero if it is to be a true zero of the function. Thus, the only unknown variable in Equation 41 was $\Delta\omega_{BW_G}$. Solving Equation 41 for $\Delta\omega_{BW_G}$ and using Equation 39 one obtains

$$\omega_{BW_G} \approx \omega_{BW_G}^* - \frac{\dfrac{\partial F}{\partial\omega_{sp}}\Delta\omega_{sp} + \dfrac{\partial F}{\partial\omega_{180}}\cdot\dfrac{\partial\omega_{180}}{\partial\omega_{sp}}\Delta\omega_{sp}}{\dfrac{\partial F}{\partial\omega_{BW_G}}}, \tag{47}$$

where the approximation sign indicates first order accuracy. Because of the first order approximation and since it was assumed that $F^c = 0$, as the solution was propagated along either the ω_{BW_G} or ω_{sp} axes, large errors could accumulate. To avoid these large propagation errors a corrector step was applied at F^c as shown in Figure 50. Many methods and algorithms have been developed which find zeros of non-linear transcendental equations. This research used the zero finder, *fzero.m*, in the program

MATLAB® [26]. The tolerance of the zero finder was on the order of 10^{-16}. The result of this corrector step was used as the next starting point for this process, becoming the new F^*. The solution was then propagated from this point in a similar manner.

Inspection of Equation 47 showed that this would be a good estimate for ω_{BW_G} except when $\frac{\partial F}{\partial \omega_{BW_G}} \to 0$. To avoid this, the technique stepped in ω_{BW_G} instead of ω_{sp}. When stepping in ω_{BW_G}, the equation used to estimate ω_{sp} was

$$\omega_{sp} \approx \omega_{sp}^* - \frac{\frac{\partial F}{\partial \omega_{BW_G}} \Delta\omega_{BW_G}}{\frac{\partial F}{\partial \omega_{sp}} + \frac{\partial F}{\partial \omega_{180}} \cdot \frac{\partial \omega_{180}}{\partial \omega_{sp}}}. \tag{48}$$

Again, this equation was a good estimate of F^c unless the denominator went to zero. If it did approach zero, the method switched back to stepping in ω_{sp}. Using this new estimate for F^c, the same zero finder was used to obtain the corrected value.

In this particular application a problem arose when using Equation 48. To calculate ω_{sp} during the estimation step or the corrector step, ω_{180} must be known. However, ω_{180} depends upon ω_{sp}—see Equation 17. To circumvent this problem, ω_{180} was calculated using the last value of ω_{sp}; ω_{sp} was then calculated using this estimate of ω_{180}. With this new value of ω_{sp}, a new ω_{180} was calculated. This process was repeated until the percent change in ω_{180} was less than or equal to 10^{-4} percent.

As alluded to previously, this method must keep track of not only which variable to step in but also in which direction. The direction of the step was easily found by determining which sector the tangent of $\frac{\partial F}{\partial \omega_{BW_G}}$ or $\frac{\partial F}{\partial \omega_{sp}}$ lied in.

By using these principles, ω_{BW_G}, which satisfied Equation 18, was calculated versus ω_{sp} for a constant ζ_{sp}. This method was then repeated at various values of ζ_{sp} resulting in a graphical representation showing the exact location of the jump line in the CAP space.

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13. ABSTRACT *(Maximum 200 words)*

Many handling qualities criteria have been developed which predict pilot opinion of landing aircraft. MIL-STD-1797A, *Flying Qualities of Piloted Aircraft*, lists six different criteria. However, applying all six criteria to one aircraft can lead to conflicting results. The Air Force Institute of Technology (AFIT) along with the Flight Dynamics Laboratory have conducted research to evaluate differences among the handling qualities criteria in MIL-STD-1797A. The overall objective of this thesis was to determine similarities and discrepancies between the Control Anticipation Parameter (CAP) and bandwidth criteria, and to evaluate the advantage of including a dropback criterion with the bandwidth criterion. Results of this research will be used to derive a more clear-cut, generally acceptable, comprehensive flying qualities criteria predicting pilot opinion for the next revision of MIL-STD-1797A.

Research was conducted in two phases. Phase I was conducted at AFIT. There the CAP domain was mapped onto the bandwidth and bandwidth with dropback criteria revealing where the criteria agreed and disagreed. Phase II was conducted at the USAF Test Pilot School. The test team used the Variable-Stability In-Flight Simulator Test Aircraft (VISTA) to simulate aircraft and obtain actual pilot opinion in the areas of agreement and conflict found in Phase I.

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